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The Management of Bridges

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Abstract

Asset owning organisations worldwide are responsible for the operation and maintenance of deteriorating stocks of bridge structures. Many of these structures are vital links within strategic infrastructure networks. Bridge managers must design and implement programmes of maintenance, repair and replacement which ensure structures remain safe and serviceable, while operating within limited budgets.

Making these decisions is complex - the data on which decisions are to be based is often incomplete, is costly to acquire and in many cases can only indirectly measure the on-going deterioration processes. Structural deterioration progresses over time in a non-linear fashion and due to a range of mechanisms. A variety of interventions are available, depending on structure condition, however, the times and condition levels at which different intervention options are viable are difficult to predict. There is huge potential for data to assist with these decisions, however this must not be blind to the sources, and inherent uncertainties, of this data.

Decisions must be made by teams and individuals within organisations and their supply chains. The design of processes and systems for asset decision making needs to recognise the roles stakeholders play, and the value of their experience.

This thesis uses a series of interviews and workshops to understand and model current bridge management practice within the United Kingdom. A large study into the reliability of visual inspection data is presented, along with demonstrations of the ways in which this data can be analysed using modern data science techniques to add value to bridge owners. Necessary developments to asset decision making processes are demonstrated through modelling of systemic behaviours, and workshops with stakeholders in existing processes.

Dedication and acknowledgements

To Becky and Billy Bennetts

When I started this project, I took it on fully expecting there'd be some long hours and late nights. What I didn't expect is that I'd be writing the final sentences with my one year old son on my lap; that those long hours would mean long hours for my wife too; and that weekends working would mean weekends that Billy didn't have his dad around. Not only have they put up with the effects my study has had on them, both of them have been there with encouragement, a smile or a hug when I need some motivation. So, thank you Becky and Billy for your love and support throughout this - I couldn't have done it without you.

Acknowledgements

I count myself as incredibly privileged to have so many exceptional, kind and talented colleagues at WSP. I'm deeply indebted to Steve Denton, whose thoughtful and balanced advice, critique and vision have been tremendously valuable throughout. I am very grateful to colleagues I have worked alongside on projects through the past five years: Mungo Stacy, Jon Shave, Steve Collard, Liam Hennessey, Hazel Mosley and Paul Hillier and many others, particularly those in the inspection team who spent nights out under motorway bridges to collect the visual inspection data! A particular mention is due to Graham Webb who has always been there with a fresh and critical pair of eyes to talk though the data, perfect a figure, or take a look through my Python code and work out what I'm doing wrong. Thanks are due also to my supervisors, Paul Vardangea, Colin Taylor and Steve Denton. In particular, Paul has gone above and beyond to closely support my work, and encourage and assist in reporting the work at conferences and in journals.

List of supporting publications

The following publications have been prepared during the course of the EngD candidature:

Technical Papers:

Bennetts J., Vardanega P. J., Taylor C. A. & Denton S. R. (2016) Bridge data - What do we collect and how do we use it? In: *Transforming the Future of Infrastructure through Smarter Information: Proceedings of the International Conference on Smart Infrastructure and Construction, 27-29*

June 2016, Cambridge, UK (Mair R. J., Soga K., Jin Y., Parlikan A. K. & Schooling J. M., eds), ICE Publishing, London, United Kingdom, pp. 531–536

Bennetts J., Webb G. T., Vardanega P. J., Denton S. R. & Loudon N. (2018b) Using data to explore trends in bridge performance. *Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction* **171(1)**: 14–28, `10.1680/jsmic.17.00022`

Bennetts J., Webb G. T., Vardanega P. J., Denton S. R. & Loudon N. (2018a) Quantifying Uncertainty in Visual Inspection Data. In: *Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges: Proceedings of the Ninth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2018), 9-13 July 2018, Melbourne, Australia.* (Powers N., Frangopol D. M., Al-Mahaidi R. & Capriani C., eds), Taylor and Francis, London, UK, pp. 2252–2259

Bennetts J., Vardanega P., Taylor C. A. & Denton S. R. (2019) Survey of the use of data in UK bridge asset management. *Proceedings of the Institution of Civil Engineers - Bridge Engineering, under review*

Bennetts J., Webb G. T., Denton S. R., Nepomuceno D. & Vardanega P. J. (2020) Looking to the future of bridge inspection and management in the UK. In: *Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges: Proceedings of the Tenth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2020), Sapporo, Australia. In Preparation.*

Professional reports:

Bennetts J., Webb G. T. & Denton S. R. (2017) *The State of Bridge Infrastructure. Technical report*, WSP UK ltd on behalf of Highways England

Bennetts J. (2016) *Support for Revised Project Prioritisation Process for Renewals Schemes, Part 2: Sub Task 4 - Scoping Study. Technical report*, WSP | Parsons Brinckerhoff, on behalf of Highways England

Stacy M. B. & Bennetts J. (2014) *Structures VMR4 Value Management Review. Technical report*, WSP | Parsons Brinckerhoff, on behalf of Highways Agency

Those publications which make up parts of chapters in this thesis are outlined in chapter 1.

Author’s declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University’s Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate’s own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: .... DATE: ....

Table of Contents

List of Tables

List of Figures

Chapter 1

Overview

1.1 Introduction

Infrastructure networks worldwide, and particularly in the United Kingdom, contain a large stock of deteriorating bridge structures, upon which ever greater demands are being placed. Meanwhile, the budgets available for the maintenance, repair and eventual replacement of these assets are limited. Many are constituent parts of vital infrastructure whose operation cannot be interrupted.

Despite many years of effort, determining the optimum level of investment in bridge management so that adequate safety is ensured, whilst network disruption and expenditure are minimised, remains a significant and largely unresolved problem. In fact, it still remains a significant challenge for bridge owners to understand the costs and consequences of adopting different management strategies. Reasons for this stem from the complexity of problem. Even considering individual structures in isolation there are a vast range of structure and element types, subject to different environmental exposure conditions and traffic loading. Their management needs to consider complementary requirements for safety, serviceability and functionality. Structural deterioration progresses over time in a non-linear fashion and due to a range of mechanisms. A variety of interventions are available, depending on structure condition. Even the current state of structures is not well known, nor can easily be determined directly, as the extent of many deterioration mechanisms can only be measured indirectly. Further, in optimising the allocation of resources, it is essential that structures are considered in the context of their role as part of a transportation network, rather than in isolation.

A further challenge relates to the way in which bridge management is done in practice - how decisions are taken and where responsibilities reside. Improving bridge management practice requires solutions that are implementable within asset owning organisations and their supply-chains.

1.2 Outline

This chapter sets out an overview of the thesis, describing the contribution of each of the chapters and highlighting any relevant publications.

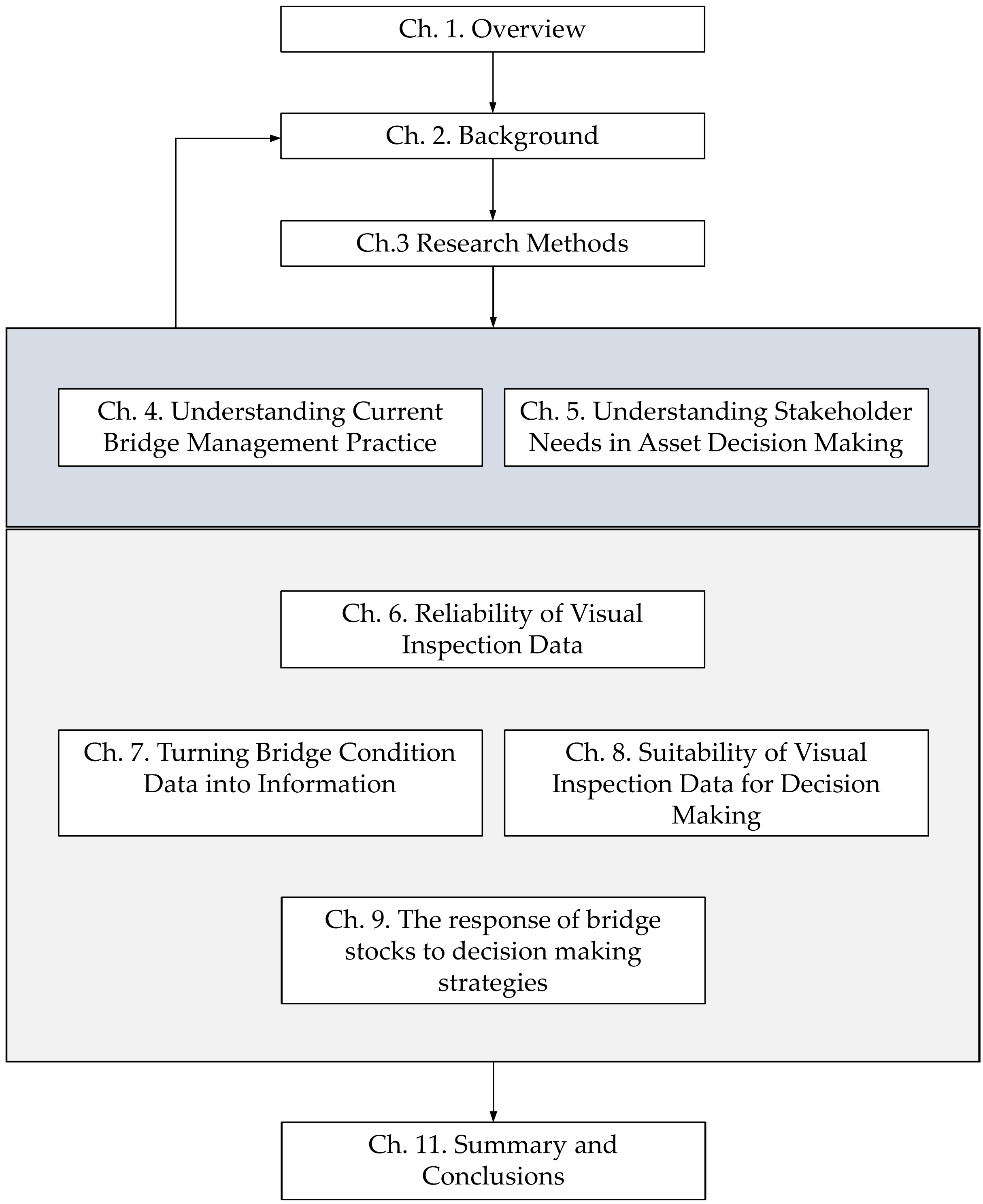

Figure 1.1: Thesis Outline

1.3 Ch. 2. Background

The literature review sets out the current state of the art in the literature, covering:

- Bridge management, its objectives, and the organisational structures responsible for it.
- Current bridge management practice, as recorded in academic literature and industry publications.
- Methods of measuring bridge performance, including visual inspection and the use of visual inspection data.
- Methods of modelling future bridge performance.
- Asset management.

Gaps in the literature are presented regarding knowledge of the existing industry application of recent developments in bridge asset data collection and use. Further, gaps are identified in the understanding of the reliability of visual inspection data for structural assets, and the ways in which this data can be usefully used to uncover trends and inform decision-making. Further research gaps are identified regarding the performance of the UK's stock of bridges; the nature of key variables needed to facilitate reliable prediction of the future performance of bridge stocks; and the needs of stakeholders in the processes that will enable decisions.

1.4 Ch. 3. Research Methods

This chapter sets out the the overall approach taken to the research. Detail is given on the particular methods used, such as Hierarchical Process Modelling and Decision Tree Learning.

1.5 Ch. 4. Understanding Current Bridge Management Practice

This chapter establishes the current state of the art of bridge management in the UK, identifies some of the industry's key challenges, and provides an insight into the various processes of which bridge management is comprised using Hierarchical Process Modelling. Analysis of semi-structured interviews with key individuals at leading bridge management organisations is presented, along with a co-developed group hierarchical process model of bridge management in the UK. Aspects of this work has been published in the following papers:

Bennetts J., Vardanega P. J., Taylor C. A. & Denton S. R. (2016) Bridge data - What do we collect and how do we use it? In: *Transforming the Future of Infrastructure through Smarter Information: Proceedings of the International Conference on Smart Infrastructure and Construction, 27-29 June 2016, Cambridge, UK* (Mair R. J., Soga K., Jin Y., Parlikan A. K. & Schooling J. M., eds), ICE Publishing, London, United Kingdom, pp. 531–536

Bennetts J., Vardanega P., Taylor C. A. & Denton S. R. (2019) Survey of the use of data in UK bridge asset management. *Proceedings of the Institution of Civil Engineers - Bridge Engineering, under review*

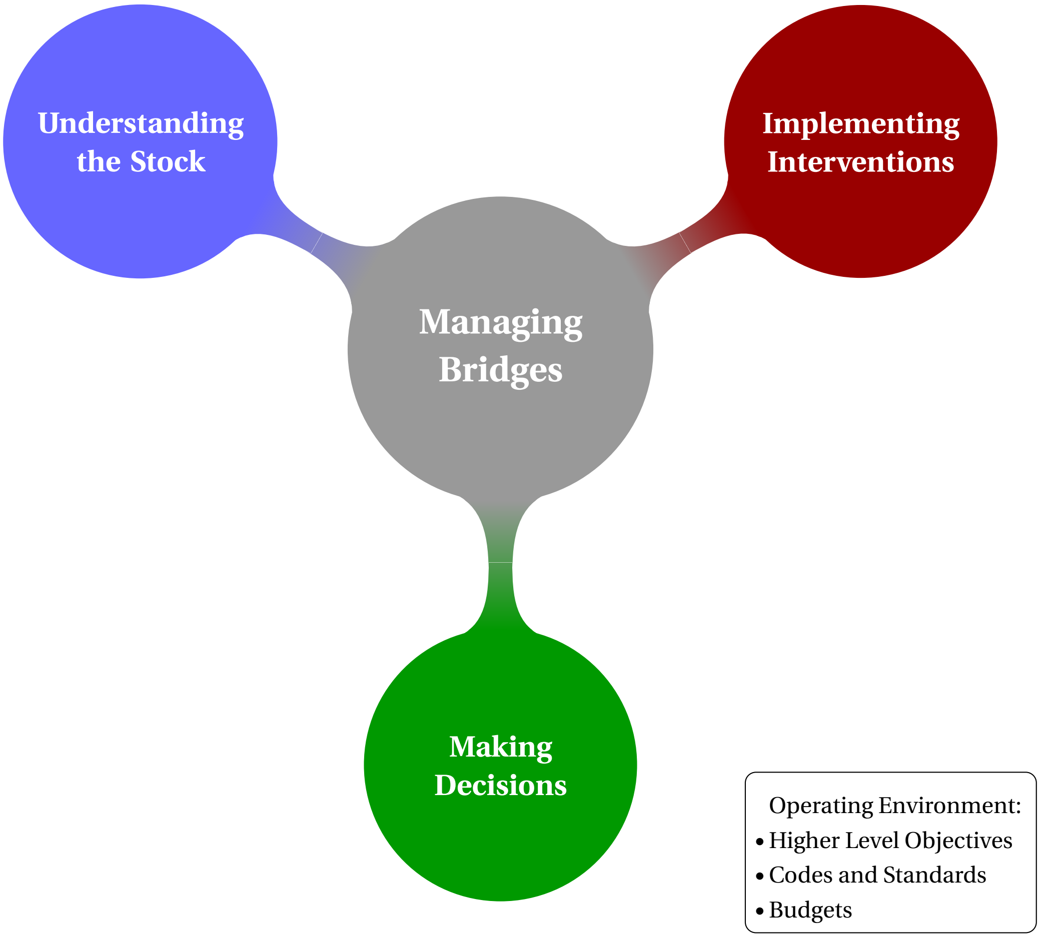

Figure 1.2: High-level model of the Bridge Management system

1.6 Ch. 5. Understanding Stakeholder Needs in Asset Decision Making Systems

Data is presented and analysed from workshops and questionnaires with 51 stakeholders in Highways England's current Value Management system, identifying desirable and undesirable characteristics of the current and a hypothetical future asset decision making process. Recommendations are made for the characteristics of an improved decision making system. Aspects of this work are based on:

Bennetts J. (2016) *Support for Revised Project Prioritisation Process for Renewals Schemes, Part 2: Sub Task 4 - Scoping Study. Technical report,* WSP | Parsons Brinckerhoff, on behalf of Highways England

1.7 Ch. 6. Reliability of Visual Inspection Data

This section reports on a study of the reliability of the data collected on the UK's highway bridges. A programme of 200 independent inspections was undertaken to review the quality of the inspections undertaken on Highways England's network and the reliability of the data recorded during them. This study was the largest ever of its kind worldwide. Significant variation was observed between individual inspector's recording of defects, and Monte Carlo methods are used to assess the effect of these on the reliability of population-level performance metrics. Aspects of this work have been published as follows:

Bennetts J., Webb G. T., Vardanega P. J., Denton S. R. & Loudon N. (2018a) Quantifying Uncertainty in Visual Inspection Data. In: *Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges: Proceedings of the Ninth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2018), 9-13 July 2018, Melbourne, Australia.* (Powers N., Frangopol D. M., Al-Mahaidi R. & Capriani C., eds), Taylor and Francis, London, UK, pp. 2252–2259

Bennetts J., Webb G. T. & Denton S. R. (2017) *The State of Bridge Infrastructure. Technical report*, WSP UK ltd on behalf of Highways England

1.8 Ch. 7. Turning Bridge Condition Data into Information

This section is based upon the research completed as part of the State of Bridge Infrastructure project Bennetts *et al.* (2017). Analysis is presented of asset condition data contained in Highways England's Structures Management Information System database, along with site observations made at a representative sample of 200 bridges across England's strategic road network. Trends in the data are observed, including compelling evidence of a reduction in the quality of construction and its effect on long-term bridge performance. Significant differences are identified between the performance of bridge assets and commonly assumed deterioration profiles. The work represents a proof-of-concept for the capabilities a future-ready asset owner should establish to enable them to draw insights from the data they collect. Aspects of the work are reported in the following paper:

Bennetts J., Webb G. T., Vardanega P. J., Denton S. R. & Loudon N. (2018b) Using data to explore trends in bridge performance. *Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction* **171(1)**: 14–28, `10.1680/jsmic.17.00022`

1.9 Ch. 8. Suitability of Visual Inspection Data for Decision Making

This chapter reviews the current and future role of data in asset management organisations, and assesses the ability of the data we currently collect to meet these needs. Significant deficiencies are presented in the industry practice of recording the current condition *state* of assets. A shift in practice, to put a much greater focus on considering and recording *change* in condition, is shown to greatly improve the utility of the collected data. Aspects of this work are published in the following paper:

Bennetts J., Webb G. T., Denton S. R., Nepomuceno D. & Vardanega P. J. (2020) Looking to the future of bridge inspection and management in the UK. In: *Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges: Proceedings of the Tenth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2020), Sapporo, Australia. In Preparation.*

1.10 Ch. 9. The Response of Bridge Stocks to Decision Making Strategies

This chapter establishes that there is significant non-linearity in the relationship between the condition of common bridge components and the cost of maintenance interventions. In particular, as component condition deteriorates, step changes are observed in the viable intervention options, with corresponding step increases in their cost. The relationship is demonstrated through a number of case-studies developed with the supply chain of a UK motorway contractor. Stochastic modelling is used to examine the impact of these findings on asset decision making strategies. Aspects of this work are presented in:

Stacy M. B. & Bennetts J. (2014) *Structures VMR4 Value Management Review. Technical report*, WSP | Parsons Brinckerhoff, on behalf of Highways Agency

1.11 Ch. 10. Summary and Conclusions

The following conclusions and impacts have been presented:

- The work has established models and filled a gap in the literature regarding current practice in bridge management in the UK.
- The work has quantified the uncertainty in bridge condition data, and its impacts on the use of that data.
- The work has shown that materials testing results do not usually provide significant additional condition information that would result in changes to the defect scores allocated by inspectors following visual inspections. (Note that the value of materials testing in designing remedial action for defects is not assessed).
- The work has demonstrated the potential for modern data science techniques to deliver value from the data held by bridge management organisations.
- The work has demonstrated the need for a change in focus of bridge inspections to place much greater emphasis on change in condition. It is likely these recommendations will be incorporated into the next generation of standards for Bridge Inspection at Highway Bridges in the United Kingdom.

- The work has identified deficiencies in typical models of bridge deterioration and intervention cost, and decision strategies to avoid them. The key conclusion is that organisations should aim to maintain assets in a steady state of good repair, rather than maintain steady spending.
- The work has identified a required re-structuring of asset decision making processes to clearly distinguish stages of 'needs identification', 'prioritisation' and 'value engineering', and to maintain, but manage, the positive contribution of engineering judgement. These recommendations have been implemented in Highways England's new Value Management system, and are being adopted across their supply chain.

Chapter 2

Background

2.1 Introduction

The management of a national infrastructure network presents a large and complex problem. Management systems must decide how best to allocate their finite resources to maintain and upgrade the network. In managing bridges, this challenge is increased by the high cost and long service lives of the assets. Typically, many of the key pieces of information required for the decision making process are uncertain, and the options for reducing uncertainty are costly and slow. The system that must make these decisions comprises an inter-connected network of technical and organisational processes embedded within an eco-system of government and commercial organisations with differing goals.

Bridge management consists of three core processes: understanding the stock; making decisions; and implementing interventions (Chapter 4). Within each of these, sub-processes have been selected for further study in the thesis. This chapter presents background information to the studied aspects of bridge management, covering:

- An overview of bridge management in the UK
- The nature of intervention options
- Methods for measuring bridge performance
- Methods for predicting the future performance of bridges
- Approaches to making asset management decisions

The chapter concludes with a discussion of the the literature and presentation of a series of Research Questions for this study.

2.1.1 Objectives of bridge management

The crux of bridge management is selecting the type and timing of interventions to ameliorate the condition or capacity of components, such that network availability is maximised and whole life cost and risk are minimised. Optimal timing of interventions is essential when striving to achieve value for money and manage risk - intervening too soon risks not deriving the full value potential from the asset, while intervening too late risks a step increase in the cost of intervention and risk. In the worst case, failure to intervene in a timely manner could result in unacceptable safety risks, such as from falling spalled concrete, obstruction in a carriageway, or ultimately structural collapse. While programming considerations, such as grouping interventions to take advantage of the economies of scale, will often affect the best value intervention timing, knowledge of the current, and likely future performance of individual elements and associated risk (both safety and financial) is required to explore these considerations in a structured way.

2.1.2 History of UK infrastructure networks

The UK's bridge infrastructure reflects the legacy of historical booms in construction, with rapid growth of the rail infrastructure between 1830 and 1900 (Bogart *et al.*, 2018) and of the motorway network in the 1960's and 70's (Chapter 7). Consequently, much of the bridge stock that now forms critical links between UK cities is ageing and deteriorated and yet must also support increased traffic load and frequency. Responsibility for maintaining the national asset is devolved to government organisations such as Highways England, Network Rail and Local Authorities. These 'client' bodies make extensive use of consultants and civil engineering contractors for advice, design and construction activity on their networks. These myriad organisations must coordinate to inspect, assess and maintain assets that are undergoing uncertain deterioration processes. The information held on the assets is incomplete - condition is inferred from 'touching distance' inspections on a six year cycle Highways England (2017), and capacity is often based on conservative assumptions and methods Denton *et al.* (2005), such as simple elastic analyses or assumed material properties.

2.2 Overview of bridge management practice

2.2.1 United Kingdom

Considering the scale of the investment that will be required in bridge assets in the coming years (E.g. Network Rail 2013, Highways Agency 2014b, Thurlby 2013)), it is important to be able to understand their current and future condition and make informed decisions on what work to do, and when. Understanding the current condition of bridge assets represents a significant challenge, with established practice being for periodic visual inspection of the structure by an experienced person. A balance has to be struck between the desire to have regular monitoring of the assets' condition and the cost and disruption to the network involved in carrying out an inspection; consequently thorough, touching distance, Principal Inspections (PI) are typically carried out at 6yr intervals (Highways Agency, 2007b). The recording of extant condition defects at a bridge is subject to the interpretation of the individual bridge inspector and their consideration of the defect type, extent and severity. Furthermore, visual inspections are often undertaken in non-ideal environmental and lighting conditions. Consequently, it is unsurprising that several studies have shown that there is considerable variation in the recording of defects between inspectors and between individual inspections (Moore *et al.* 2001b; Lea & Middleton 2002).

Several approaches have been proposed to optimise spending on the management of infrastructure assets and to address the inherent uncertainties in the decision making process. Many authors have proposed systems for predicting the future condition of bridges based on imperfect current data (e.g., Enright & Frangopol 1999), and such processes are reported to be in use by bridge owners internationally (Mirzaei *et al.*, 2012). Others propose decision support tools which consider evidence for current performance, such as inspection data and historic failures, and explicitly present the uncertainties to give an overview of current performance which could be used to inform future management (Hall *et al.*, 2004).

The ownership of bridge assets in the UK is split based upon transport mode, strategic importance, and location. The management of these assets is often further delegated to contractors, with specialist sub-contractors and consultants frequently picking up more complex work, load-rating assessments and renewal designs. The consequence of this is that asset data collection and decision making processes across the bridge stock are highly heterogeneous, with no clear view of current practice available in standards or the literature.

2.3 Maintenance interventions

2.3.1 Types of maintenance interventions

Interventions to repair, replace or enhance structures are the primary tool of bridge management organisations in discharging their obligations to maintain infrastructure networks in a safe and serviceable condition. Bridge managers must plan programmes of maintenance and renewal schemes to mitigate risks to the safety and serviceability of their structures, while operating within an agreed budget.

The are several drivers for inclusion of interventions on a maintenance programme (based on, e.g. Highways Agency 2014a, UK Roads Liaison Group 2016, LoBEG 2018):

Safety Maintenance interventions to correct immediate safety issues to the asset user, or address deficiencies in a structure's ability to resist predictable accidental loading (such as collisions from errant vehicles), or susceptibility to natural hazards (e.g. scour or fire). For example, removal and repair of loose spalled concrete that may fall onto a railway; or replacement of a heavily corroded bridge parapet.

Functionality Schemes designed to ameliorate deficiencies in the ability of a structure to support the required loads (capacity), traffic flows. For example, strengthening of a bridge deck that is assessed as being sub-standard due to deterioration and is subject to a load restriction to restore a full 40T load rating. Note that if the structure was not subject to a marked load restriction then this would be a safety scheme.

Aesthetic Schemes to remedy appearance defects, such as graffiti and deteriorated paint systems.

Environment Work to correct on-going damage to the environment, including ecological impacts, local air and noise pollution. In practice, there are few examples where bridge maintenance would be required.

'Value for money' or preventative Schemes where an intervention is predicted to reduce expenditure over the lifetime of the asset, or reduce risks to the network. For example, repainting steel beams to avoid corrosion damage, or repair of deck joints and seals to prevent damage caused by water leakage.

Value for money schemes are a special case, in that their justification is based on putting a 'stitch-in-time' to avoid having to undertake work reactively because of one of the other justifications, for example, repainting steel beams to prevent loss of capacity due to corrosion. If asset performance could be reliably predicted and there was no maintenance backlog, all schemes would be preventatively planned and be justified on a value for money basis. Under such an idealised regime the assets would never reach a condition where a reactive scheme is required. However, the current situation for many asset owners is that every year there is more asset need for reactive schemes than there is resource to address them. A process of prioritisation is therefore required, and it can be hard to justify prioritising preventative schemes over those which address an extant safety, environmental or functionality issue. The result is that, if an asset stock's condition falls below good state of repair, organisations can get stuck in a year-on-year 'fire fighting' exercise, without the funds to invest in preventative schemes with a whole life cost benefit. This downward spiral is sometimes refered to as an 'asset management time-bomb' (Thurlby, 2013).

2.3.2 The relationship between condition, intervention options and cost

Some studies adopt a simple proportional relationship between the condition of an asset and the cost associated with returning an asset to a better condition (e.g. LoBEG 2009, Ryall 2010, P.365, Yanev & Richards 2013, Atkins 2015). This model may be valid for some bridge components, where there is only one intervention option, and where the cost of that intervention option increases in inverse proportion to the condition of the component. However, for many bridge components, there are multiple intervention types that might be deployed, depending on the condition. Consider the example of a maintaining a timber window frame, the available maintenance interventions could be summarised as follows:

Touch-up Clean and touch-up damaged areas of paintwork.

Repaint Lightly sand to remove any loose paint, and then repaint whole window frame.

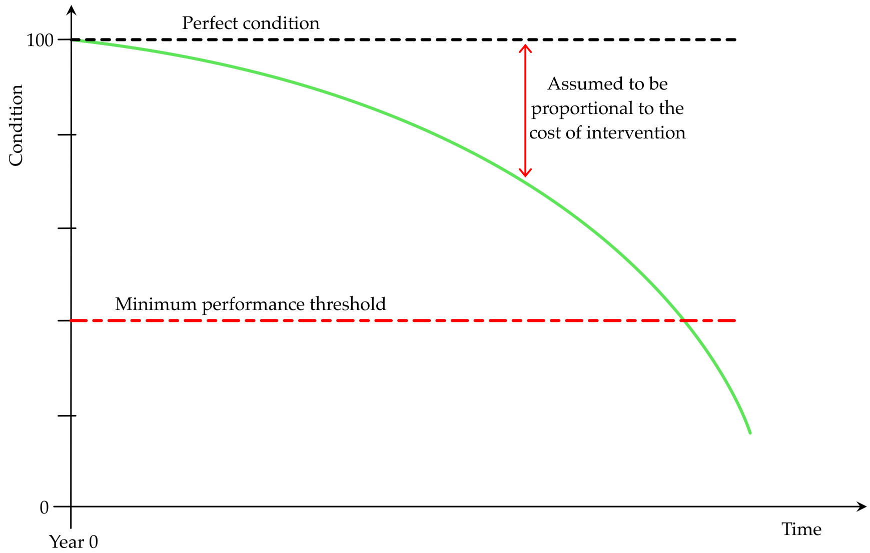

Figure 2.1: In the simple cost-condition relationship often used in the literature, the cost is assumed to be inversely proportional to the condition. (Based on, for example, Ryall 2010, LoBEG 2009, CIRIA 2009)

Minor repairs and repaint Undertake minor wood repairs (remove rotten timber, fill with filler) and repaint.

Repairs and repaint Undertake wood repairs (cut back timber, splice in new wood, fill, sand) and repaint.

Replace Replace the window frames.

Emergency Windows suddenly fail, and require urgent repair to remain in service ahead of replacement.

Each intervention option is significantly more costly than the last and each option is only viable up to a certain condition threshold, beyond which only the more disruptive and costly options are available. Also, some interventions are inappropriate if the condition is good - you can't do wood repairs if there is no wood to repair. So, there is a *window* of opportunity for different maintenance options. The cost-condition relationship in this example is non-linear, with sudden step increments in cost, and a quick touch-up many times cheaper than full replacement. Common bridge components exhibit a similar progression of intervention options from low-cost preventative maintenance options (such as greasing bearings, or applying hydrophobic surface impregnants to concrete), through major interventions and strengthening, to replacement of whole components. In the emergency case, choice in intervention timing is removed as works must be undertaken immediately to maintain functionality. Approaches which account for the differences in available intervention options have been adopted by the Federal Highways Authority (Thompson *et al.*, 1998) and have been used in the literature (e.g. Neves & Frangopol 2005). Appendix A presents the costs associated with deferral of maintenance interventions for four case studies, and demonstrates that for common examples, reactive maintenance can cost more than five times as much as planned preventive options.

In recent UK examples where it would not be acceptable for a critical infrastructure asset to be allowed to fail or removed from service, funding has been found to pay for emergency works, even where these exceeded the allocated budget (e.g. New Civil Engineer 2012a, New Civil Engineer 2012b, Transport for London 2015, BBC News 2016, Collins *et al.* 2018). Structures falling to a condition where costly and disruptive emergency work are required is one of the primary risks for a UK bridge owner. In practice collapse due to deterioration is rare in the UK - the most recent examples being the collapse of Stewerton Bridge in 2009 due to corrosion of the webs of the main wrought iron beams (RAIB, 2010) and before that the collapse of Ynas-y-gwas bridge in 1985 due to deterioration of post-tensioning tendons (Woodward & Williams, 1988). However, collapse due to deterioration remains a significant concern in countries where the bridge stock is in poorer condition (e.g. Bazzucchi *et al.* 2018), and collapse is the ultimate risk to any bridge stock.

2.4 Measuring bridge performance

2.4.1 Condition monitoring

The most common method of condition monitoring used to assess and record the condition of bridge assets in the UK is visual inspection (Highways Agency, 2007b), which can be seen as a form of 'damage detection' in the wider framework of structural health monitoring systems (Webb *et al.*, 2015). For UK highway structures, bridges are typically visually inspected from within 'touching distance' every six years, although some organisations allow the frequency to be adjusted on a risk basis (Highways England, 2017). Any defects found are recorded against a component of the structure and classified by their type, severity and extent (Highways England 2017; TSO 2007). Similar systems are used for rail structures (Network Rail, 2017), London Underground (McKoy, 2016), and globally (e.g., Graybeal *et al.* 2002; Kruger & Nyokana 2018). In current UK highway sector practice (Highways England, 2018), the severity of defects is recorded on a scale from 1 to 5 (Table 1), and the extent is recorded on a scale from A to E, corresponding to a score from 0 to 0.7 (Table 2). The severity and extent scores for the most severe defect on a component are added together to provide a numerical representation of the condition of that component.

Visual inspection is the primary form of condition monitoring that is currently operated by bridge owners in the UK (e.g. Lea 2005, Middleton 2004, McRobbie *et al.* 2015, Bennetts *et al.* 2016), however, studies of the reliability of visual inspection have shown that the recorded data can be subject to significant uncertainty due to human factors (e.g. Moore *et al.* 2001b, Lea & Middleton 2002). Moore *et al.* (2001b) compared data from 49 different inspectors across 10 inspection tasks, comprising routine inspection of seven bridges and in-depth inspection of three bridges on the disused Pennsylvania Turnpike highway in the USA. Moore *et al.* (2001b) concluded that the experience and physical capabilities of inspectors, and the environment in which inspections were undertaken, had significant influence on the reliability of the inspection data recorded.

The data collected during visual inspections is increasingly used to inform decision-making (see chapters 4, 7 and 9), both at an individual structure level and at a strategic, whole stock level (e.g. British Standards Institution 2014a, UK Roads Liaison Group 2016). It is important to understand the reliability of the underlying data and its implications for the reliability and utility of derived *Condition Performance Indicators*, on which strategic decisions may be based.

2.4.2 Inspection data

The industry practice for visual inspection of UK highway bridges is for a cycle of 'General Inspections' every 2 years, with 'Principal Inspections' every 6 years (Highways Agency, 2007b). During these inspections any defects observed on the structure are noted and photographed and recorded digitally later on. These defects are assigned to individual components in the bridge inventory and, for each defect, the defect type is recorded along with a severity code (the options for which are set out in Table 2.1) and an extent code from *SA* to *SE* (Table 2.2). Severity codes are categorised into different severity types, according to the defect type (Table 2.3), and are suffixed with an *S* if they are considered to present an immediate safety concern. Defects observed during inspections of bridges on the Highways England network are entered into the Structures Management Information System (SMIS) database.

Table 2.1: Mapping of Severity Codes to Severity Scores. (Based on the SMIS User Guide, (Highways England, 2018), and the County Surveyors' Society condition score system (Sterritt & Shetty 2002, Atkins 2007))

Severity Codes				Severity
D	P	A	X	Score
D1	P1	A1	X1, X2	1
		A2		1.1
D2	P2	A3	X3	2
D3	P3	A4	X4	3
D3S			X4S	3.1
D4	P4		X5	4
	P4S			4.1
D4S				4.2
D5	P5			5

2.4.3 Condition performance indicators

In order to monitor the overall condition of individual structures or stocks of bridges, it is necessary to derive a measure of 'condition' from recorded defect information and the structure inventory. The *Bridge Condition Indicator* was developed for this purpose by WS Atkins Ltd (Sterritt & Shetty 2002, Atkins 2007) for the County Surveyors' Society (CSS, now the Association of Directors of Environment, Economy, Planning and Transport, ADEPT) in the UK, and is adopted as a metric to score the condition of a bridge asset, or a population of assets, by most highway bridge owners in the UK. An understanding of the way in which the *Bridge Condition Indicators*, BCI_{Ave} and BCI_{Crit} are calculated is critical to understand the implications of the results presented in this chapter. The process that is used by Highways England in SMIS is slightly different from the original CSS process (Sterritt & Shetty, 2002) and is set out as follows:

Table 2.2: Mapping of Extent Codes to Extent Scores. (Based on the SMIS User Guide, (Highways England, 2018), and the County Surveyors' Society condition score system (Sterritt & Shetty, 2002))

Extent Code	SA	SB	SC	SD	SE
Extent Score	0	0	0.1	0.3	0.7

Table 2.3: Defect Severity Types. (Based on the SMIS User Guide, (Highways England, 2018), and the County Surveyors' Society condition score system (Sterritt & Shetty 2002, Atkins 2007))

Defect Severity Type	Description
D	Damage causing defects
P	Paint coating and protective system defects
A	Appearance related defects
X	Defects affecting adjacent areas

1. Defects in SMIS are recorded against individual components. Each defect score comprises a severity code and an extent code. These codes are mapped to numerical scores as shown in Tables 2.1 and 2.2.

2. For each component the defect with the highest severity score is selected. If there are multiple defects with the same severity then the defect with the highest extent score is selected.

3. All other defects on that component are disregarded.

4. For each component type, only defects with the same severity as the most severe are included.

5. A weighted average extent score based on the total size of all the components of that type is calculated.

6. The extent and severity scores are added to calculate an Element Condition Score (ECS) for each component type, on a scale from 1 to 5.7.

7. The Element Consequence Factor (ECF) for each component type is calculated from the ECS and the component's importance as shown in Table 2.4.

Table 2.4: Mapping of Element Consequence Factor (ECF). (Based on the SMIS User Guide, (Highways England, 2018), and the County Surveyors' Society condition score system (Sterritt & Shetty 2002, Atkins 2007))

Component Importance	Element Consequence Factor (ECF)
Very High	0.0
High	$0.3 - [(ECS - 1) \times 0.3/4]$
Medium	$0.6 - [(ECS - 1) \times 0.6/4]$
Low	$1.2 - [(ECS - 1) \times 1.2/4]$

8. The Element Condition Index (ECI) is found by subtracting the ECF from the ECS. The ECI cannot take a value below 1.0.

9. The Element Importance Factor (EIF) is determined based on the importance of the component type, as shown in Table 2.5.

Table 2.5: Mapping of Element Importance Factor (EIF). (Based on the SMIS User Guide, (Highways England, 2018), and the County Surveyors' Society condition score system (Sterritt & Shetty 2002, Atkins 2007))

Component Importance	Element Importance Factor (EIF)
Very High	2.0
High	1.5
Medium	1.2
Low	1.0

10. The Average Bridge Condition Score BCS_{Ave} is calculated by averaging the ECI values, weighted by the EIF for each component type.

11. The Critical Bridge Condition Score BCS_{Crit} is found by taking the maximum ECS for all 'Very High' Importance components.

12. BCS_{Ave} and BCS_{Crit} are both scores between 1 (best condition) and 5 (worst condition). These are mapped using an assigned quadratic function to give Bridge Condition Indicators BCI_{Ave} and BCI_{Crit} between 0 (worst condition) and 100 (best condition). The mapping functions are shown in Equations 2.1 and 2.2.

$$BCI_{Ave} = 100 - 2[{BCS_{Ave}}^2 + 6.5BCS_{Ave} - 7.5] \tag{2.1}$$

$$BCI_{Crit} = 100 - 2[BCS_{Crit}{}^2 + 6.5BCS_{Crit} - 7.5] \tag{2.2}$$

(Based on the SMIS User Guide, (Highways England, 2018), and the County Surveyors' Society condition score system (Sterritt & Shetty 2002, Atkins 2007))

To calculate stock level BCI scores these steps are repeated for all bridges in the stock and an average is taken, weighted by each structure's deck area.

2.4.4 Structural investigations and testing

More involved investigative methods are often assumed to provide valuable additional information beyond that available from visual inspection techniques. Non-destructive techniques such as ground penetrating radar (The Concrete Society, 1997), x-ray, ultrasonic scanning and ferrometric scanning (Gaydecki *et al.*, 2000) have been demonstrated to assist in resolving unknowns surrounding, for example, layout of steel reinforcement within concrete structures. More intrusive semi-destructive structural investigations are frequently used to determine the chemical properties of in-situ concrete (Highways Agency, 1990) such as:

- Phenolphthalein testing for carbonation (Concrete Bridge Development Group, 2002);
- half-cell potential testing and chloride testing to understand the likelihood of corrosion of embedded reinforcing steel (Concrete Bridge Development Group, 2002);
- petrographic analysis to diagnose internal degredation of concrete due to processes such as Delayed Ettringite Formation, Alkali Silica Reaction and Thaumasite (The Concrete Society, 2010).

Post-tensioned concrete structures are required to be subject to Post-Tensioned Special Investigations (PTSI) (Highways England, 2015), to assess the condition of the tendons and presence of protective grout. These PTSIs involve gaining access to the tendon ducts in a structure, typically using power drills to remove a core down to the duct, and then endoscopes to investigate the tendons within each duct.

The condition and deterioration of structures is not strongly linked to the mechanical properties of their constitutive materials, however, these may be tested for use in load-rating assessment calculations to understand the load capacity of an existing structure. Common tests include:

- testing of concrete core samples for compressive strength and tensile strength in splitting and bending tests;
- coupon testing of samples of steel sections or reinforcement to establish yield stress, ultimate stress and strain to failure;
- pull-off and scratch testing of paint systems to establish bond to the substrate and condition;
- pull-off testing for bonded elements.

2.4.5 Technology and structural health monitoring systems

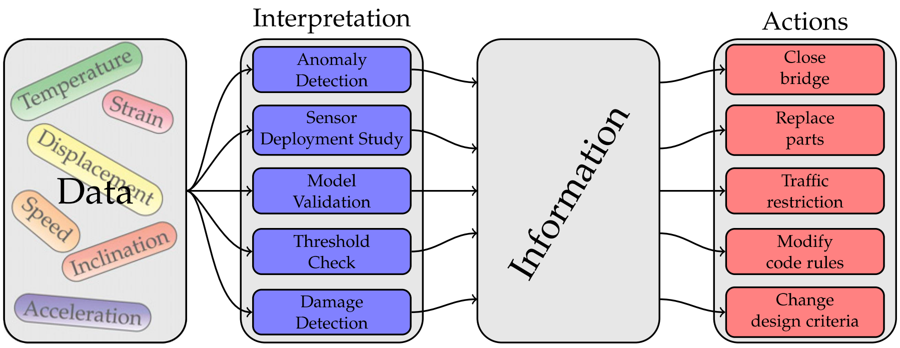

Figure 2.2: Structural Health Monitoring (SHM) implementation process proposed by Webb *et al.* (2015), showing the categories of SHM and flow from data to action. (taken from Webb *et al.* (2015))

Various technological solutions, and particularly Structural Health Monitoring (SHM) systems, have been proposed to supplement or replace visual inspections as a source of bridge condition data (e.g. McRobbie *et al.* 2015; Koch *et al.* 2015). These systems promise to offer dramatically improved data collection intervals, more objective and repeatable data, reduced network disruption, and measurement of variables that is not possible with visual inspection (e.g., Hoult *et al.* 2009). Webb *et al.* (2015) undertook a thorough review of the literature across various techniques available for Structural Health Monitoring in 2015, covering: traditional strain gauge techniques; fibre optic strain measurement; computer vision; and MEMS sensors. Since Webb *et al.*'s review, there have been significant advances in the use of radar spectrum satellite monitoring of bridges, which shows significant potential for the monitoring of bridges at risk of scour (Selvakumaran *et al.*, 2018), and some potential to augment traditional bridge monitoring systems (Selvakumaran *et al.*, 2019). Further advances have also been made in the application of computer vision and machine learning (Cha *et al.*, 2017), with recent demonstrations showing the techniques are now accurate enough that it is possible to capture displacements so small that audio can be recovered from observed vibrations of surrounding materials (Davis *et al.*, 2014), and dynamic structural vibration modes can be identified using a smartphone camera (Davis *et al.*, 2017). Such techniques are interesting and do have some application to bridge management (e.g. monitoring stresses in fatigue-limited bridges, see Chapter 4). However, it can be shown (Webb, 2014) that very high accuracy in displacement or acceleration measurement would be required to meaningfully measure damage to typical bridge structures with these methods.

2.5 Modelling future bridge condition

2.5.1 Approaches to modelling deterioration

Predicting the future performance of assets, and modelling the deterioration paths of common components, and the corresponding nature and cost of interventions required to return them to a state of good repair, is a necessary component of a modern bridge management organisation (Woodward et al. 2001; ISO 2014). However, this represents a significant technical challenge. There are three general approaches used by bridge managers to predict the future performance of their assets:

1. expert judgement and experience;
2. modelling based on theoretical models of specific known physical deterioration processes;
3. empirical methods using records of the historic performance of similar assets.

In practice, most modern Bridge Management Systems adopt aspects of all three approaches, albeit with differing focuses. For example, in the case of concrete elements, the Pontis system (Thompson *et al.*, 1998) developed by the Federal Highway Administration in the United States uses a physical model of the ingress of chlorides, based upon each structure's salting frequency, cement content and reinforcement cover (Babaei 2003; Gaal *et al.* 2003). Similarly, in the UK, the water industry uses chloride and sulphate ingress models to predict concrete deterioration. However, this approach requires knowledge of several technical and operational details about the structure that are not typically known for existing structures nor are they likely to be collected for new structures as they are not included in UK standards for highway asset records (Highways Agency, 2007a). In contrast to the physics-based models used to model concrete deterioration in Pontis in the USA, the UK's CIPFA toolkit, adopted by local authorities and closely related to Highways England's Structures Investments Toolkit, uses deterioration profiles calibrated through expert judgement and experience (Atkins, 2015).

2.5.2 Deterministic vs probabilistic models

The CIPFA toolkit is based on deterministic models which assume all elements of a given type, material and exposure follow exactly the same deterioration path, which can be considered to be the mean of the range of expected deterioration. The advantage of this approach is that it can allow a specific time to failure or maintenance to be predicted for individual elements, with the trade-off being that the known variation in elements' performance (due to both aleatoric and epistemic uncertainties) is neglected. The main alternatives to deterministic approaches are probabilistic models, which are in use by some asset management organisations. Such models typically include probabilities of transfer from each condition state to all other worse states (Sobanjo 2011; Thompson *et al.* 1998). A key challenge with such models is in having sufficient data to justify the model parameters. There are additional challenges in aligning adopted deterioration models to the discrete values assigned according to qualitative defect descriptors used in the defect recording process.

2.6 Making asset management decisions

2.6.1 Lifecycle management

Consideration of the full asset lifecycle is established practice in bridge asset management (e.g. Ryall 2010) and is mandated by industry standards such as BS ISO 55000 Asset Management: Management Systems - Requirements (British Standards Institution, 2014b), and BS ISO 15686-5:2017 Buildings and constructed assets - Service life planning, Part 5: Life-cycle costing (BSI, 2017). Decisions to build new assets or for the maintenance, repair and renewal of existing structures are made on the basis of which option has the lowest whole life cost, or if benefits are considered, the highest whole life value. The 'Client' organisations also have their own standards which set out requirements for design to consider the long-term performance of their assets and ease of maintenance e.g. BD57/01 Design for Durability (Highways Agency, 2001).

Best practice lifecycle assessment in the UK includes consideration of non-cost measures such as environmental impacts and user-cost (cost associated with traffic delays) and is set out in a guide complied by the London Bridge Engineering Group (LoBEG), which represents the bridge owners in London (LoBEG 2009, LoBEG 2018). It should be noted, however, that some of the major bridge owners do not yet include non-cost measures in their consideration of schemes: for example, the Highways Agency's Value Management Process (Annex D of the Portfolio Control Framework Handbook) only considers the net present costs of a scheme, neglecting the possible user and environmental benefits (Highways Agency, 2014a).

2.6.2 Bridge Management Systems

Over the last two decades, bridge owners have implemented computer-based information systems to record their inventory information and, usually, information on the condition of their structures (Mirzaei *et al.*, 2012). These database systems, known as Bridge Management Systems (BMS), hold records of defects found during routine inspection activities and can be used by the bridge owner to plan future maintenance throughout the asset lifecycle. Some systems, such as Pontis developed by the US Federal Highway Administration, include probabilistic methods to predict the deterioration of structures and dynamically plan and programme maintenance work (Thompson *et al.*, 1998). The aim is to optimise for a reduction in the overall cost of maintaining a stock of bridge assets, however, there is still active debate as to whether the processes used can accurately predict deterioration rates and reduce costs (Liu & Madanat, 2014). Flaig & Lark (2000) published a study of Bridge Management Systems in the UK after conducting an extensive set of interviews and concluded that "*... current systems are often too theoretical in the approach they take to the practical task of managing a bridge stock ...*". Nonetheless, there is on-going development of bridge management systems to include more accurate methods of automatic lifecycle management of assets (Agile Assets, 2015) and to include mobile technologies to facilitate on site data interrogation and entry, by multiple stakeholders (Hammad *et al.*, 2006).

2.6.3 Making asset decisions based on Benefit Cost Ratios

Where preventative schemes need to compete for funds with those that have other primary justifications, such as immediate safety concerns, a system of weightings is required to compare schemes on a unified scale. This approach is a 'Weighted Sum Method' of Multi-Criteria Decision Analysis (Triantaphyllou, 2000). These weightings are usually empirical and in the best cases should be derived and calibrated by stakeholders in the process (see chapters 4, & 5 and Bennetts *et al.* 2019, CIRIA 2009). While there are examples of organisations attempting to obviate these weightings by converting risks to a monetary value (LoBEG, 2018), in practice, because of the uncertainty and subjectivity in converting many of the factors to a monetary value, the net effect is the same. Indeed, there is a disadvantage in this approach that the weightings used are buried in the currency conversion process, and not explicitly stated as weightings that can be revised as experience with the system is gained, or strategic priorities are updated.

If an economic argument is to be put forward to justify an increase in expenditure to fund preventative maintenance, or justify prioritisation of preventative schemes at the expense of reactive schemes, then it is necessary to be able to quantity the benefit of undertaking a preventative scheme. The most common practice amongst bridge owners is to use a Benefit Cost Ratio (BCR) to quantify the financial benefit in terms of whole life cost saving per pound of expenditure now (e.g. CIRIA 2009, Highways Agency 2014a, BSI 2017). This is the method mandated for use with all UK government expenditure (HM Treasury, 2018). For a preventative maintenance scheme, the benefit is the money saved i.e. the difference between the whole life cost (WLC) of not doing the scheme, and the whole life cost of doing the scheme:

$$BCR = \frac{\text{WLC of not doing the scheme} - \text{WLC cost of the scheme}}{\text{Current cost of the scheme}} \tag{2.3}$$

The whole life cost of not doing a scheme is the WLC of doing the minimum possible to keep the structure in service, the so-called 'do minimum' option. Making the assumption that all the costs of the scheme are in year 1, then the WLC of the scheme is the same as the current cost and Equation 2.3 can be rewritten as:

$$BCR = \frac{WLC_{DoMin}}{\text{Current cost of the scheme}} - 1 \tag{2.4}$$

The 'do minimum' option is often the same scheme, deferred by a year, which can lead to a tendency for processes based on BCR principles to perpetually defer interventions. The implications of this on decision making and the risk of perpetual deferral of schemes is discussed in Section 9.2.

2.6.4 Accounting for uncertainty in decision making

A fundamental challenge in the management of bridge assets is the uncertainty in key parameters such as condition and capacity and their rates of deterioration. There has been significant research interest in the use of statistical approaches to manage the uncertainty in asset management processes. Internationally, there have been several studies on the application of Bayesian statistics to the management of bridge stocks (e.g. Enright & Frangopol 1999, Sloth *et al.* 2002, Rafiq *et al.* 2014). Concurrently, methods have been developed using Interval Probability Theory, visualised using an 'Italian Flag' and hierarchical process modelling (e.g. Hall *et al.* 2004, Davis & Hall 2003, Harding *et al.* 2004). Blockley argues that these methods offer advantages over a Bayesian approach (Blockley, 2013). A particular advantage of Blockley's work is treatment of epistemic uncertainties - the things we do not know, and (as Donald Rumsfeld put it in 2002) *'unknown unknowns - the things we do not know we don't know'*. This is in stark contrast to the majority of other approaches, which treat all uncertainty as aleatory. Indeed, there appears to be an ontology in much of the literature that all uncertainty is known or knowable and aleatory. This has resulted in positivist epistemologies that seek to model all unknowns as random variables with known distributions (e.g. Neves & Frangopol 2005, Neves *et al.* 2006, Sobanjo 2011). Under these research paradigms, bridge management could be 'solved' if research establishes the parameters for each of the probability distributions. As Blockley (2013) and Hall *et al.* (2004) observe, these Bayesian approaches will struggle to deal with complex socio-technical problems due to their inability to model unknowns and unknown-unknowns.

2.7 Discussion and research questions

The system of bridge management in the UK is devolved across multiple organisations, whose operational practices and policies are not widely documented in the literature. There are several reports of potential decision making and decision support methodologies, however it is not clear which of these if any are adopted in practice. This uncertainty in the current system of management and operations leads to Research Question 1, which seeks to fill the gaps in available literature surrounding current practice within bridge management organisations in the United Kingdom. There has been a significant volume of research activity and literature surrounding the use of Structural Health Monitoring to inform and potentially automate intervention decision making. However, despite case studies in the literature, it is not clear whether this research activity is translating into industry practice.

Research Question 1. *What is the current system of bridge management in the United Kingdom?*

Sub Question 1.1. What processes are involved in the management of bridges?

Sub Question 1.2. What data is collected by asset owners?

Sub Question 1.3. How are decisions made?

Visual inspection is the most common form of performance measurement for bridge assets worldwide, and there are many studies in the literature that propose the use of this condition data to predict future performance and assist in decision making. However, there have only been a limited number of studies into the reliability of this data, and there is concern in the industry following the Moore *et al.* (2001b) study in the United States. There are no published studies relating to the reliability of visual inspection data collected in the Severity-Extent format used by UK bridge owners - this is the motivation for Research Question 2. Interview candidates (see section 4) noted concerns regarding the competency of inspectors, and the industry has recently introduced the Bridge Inspector Competency scheme (Lantra, 2015), however, there is no evidence in the public domain of whether inspections are being undertaken by suitably experienced personnel and in accordance with the standards and guidance. There has been a varied history of the use of additional testing to complement visual inspection in the UK, with a requirement for testing alongside inspections having been introduced, and subsequently withdrawn.

Research Question 2. *How reliable is visual inspection data?*

Sub Question 2.1. Are bridge inspections being carried out competently?

Sub Question 2.2. What factors affect the reliability of visual inspection data?

Sub Question 2.3. How does testing contribute to a bridge owner's understanding of asset condition?

With Bridge Management Systems, and the current paradigms for the recording of visual inspection results having been implemented in the early 2000's, bridge owners in the UK now have valuable databases of information that may be used to inform their decisions and policies.

Research Question 3. *What information can be gained from historic asset condition data?*

Sub Question 3.1. How should existing data be interpreted?

Sub Question 3.2. Can trends be identified in existing data?

Sub Question 3.3. How effective is the asset condition data that is collected for informing decision making?

The literature presents many approaches for asset decision making systems and methodologies, however these do not appear to be widely adopted in practice (Chapter 4). It is not clear what effect application of the Benefit Cost Ratio (BCR) decision making approaches that are applied to individual structures in practice will have on the long term performance of bridge stocks.

Research Question 4. *How should asset management decisions be made?*

Sub Question 4.1. How well do current decision making processes work, and what are their effects on long-term stock performance?

Sub Question 4.2. What factors should be considered in the design of asset decision making processes?

Chapter 3

Research Methods

3.1 Research methods

3.1.1 Research paradigm

The research in this thesis has been conducted using a mixed-methods approach (Mingers & Brocklesby, 1997). A good summary of research paradigms is presented in Saunders *et al.* (2009b). Overall, a research paradigm has been adopted with methodologies adopted from positivist (i.e. approaches that rely on scientific evidence, such as experiments and statistics to answer research questions) and phenomenological research traditions (i.e. approaches typically used in the social sciences that use inductive, qualitative methods such as unstructured interviews and observation to gain an understanding of the experiences and perceptions of individuals (Saunders *et al.*, 2009b)). The approaches used varied depending on the research question and the available sources of information. For example, while the majority of the research questions are deductive in nature, a more inductive, grounded-theory (Glaser & Strauss, 1967), approach was taken to the interviews in chapter 4. In practice, this meant that as the interviews were processed, the transcripts were not solely assessed (coded) against pre-determined research questions, instead the research questions were updated and added to in response to the interviews. It also meant that the emergent results from the interviews were were fed back in as an extension of the the literature review to develop further 'grand-tour' research questions which are the focus of later chapters. In the later chapters the research questions were treated in a traditionally-scientific deductive manner, with evidence sought to respond to the research questions.

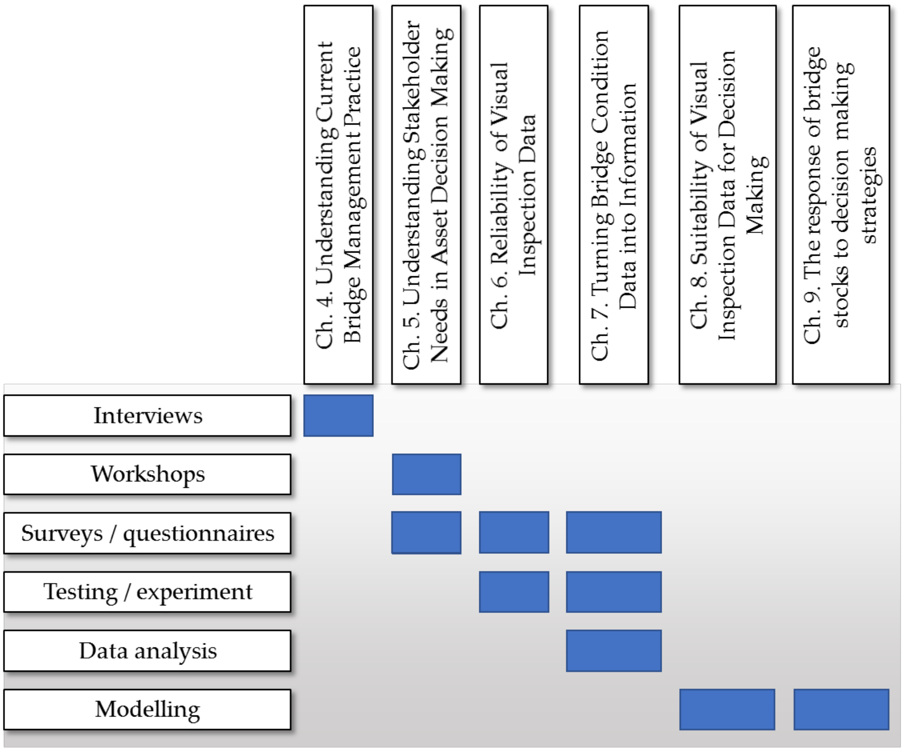

Figure 3.1: Overview of the research methods adopted in each chapter

3.2 Qualitative data analysis

Qualitative data was generated through interviews in chapter 4, workshops in chapter 5, and the site observation notes in chapters 6 and 7. The objective for designing the methodology for processing this data was to ensure that the results are repeatable and audit-able, and that if the exercise were to be repeated the results ought to be the same. In the social sciences, qualitative data analysis is the norm, and there is extensive text book advice on designing interview protocols (Oppenheim, 1992), surveys and in analysis of the results (Saunders *et al.*, 2009a). The usual practice is to review interview transcripts or other qualitative text, highlighting excerpts of text that relate to each research question or theme (Fielding, 2016). The current state of the art is for this process to be done digitally, assigning 'codes' to the excerpts of text with a pack of virtual highlighters. This process is referred to as Computer Assisted Qualitative Data Analysis, or CAQDAS (Lewis, 2016).

The online CAQDAS package 'Dedoose.com' was selected for use in this project because it has a streamlined interface for transcribing and coding audio files simultaneously. The work flow adopted was as follows:

1. The coding environment was set up with the research questions and themes.

2. Then the files were processed, highlighting snippets which relate to the research questions (Figure 3.3).

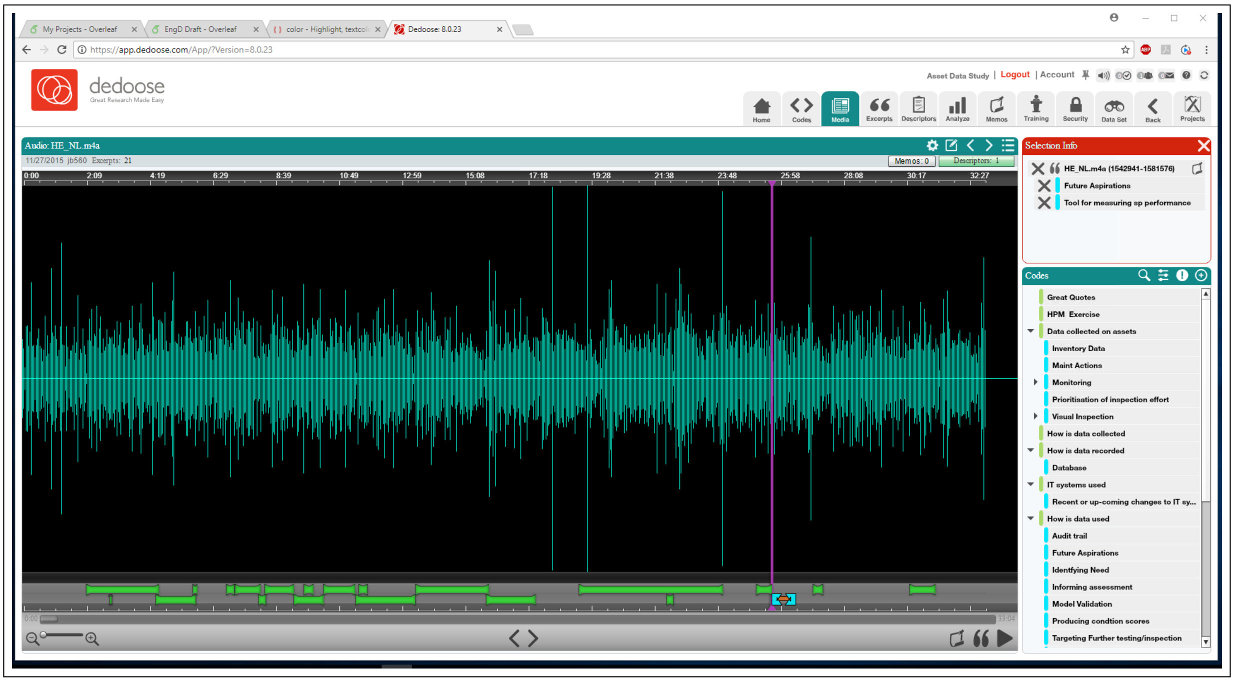

Figure 3.2: Audio coding interface in Dedoose.com

3. The research questions were refined and added to as each file was processed.

4. The codes were reviewed and rationalised.

5. Each file was re-analysed with the updated set of codes.

6. Finally, reports for the excerpts relating to each code were generated and used to build narratives and present findings.

The process was iterative, repeating steps 2 to 5 by going through the files and adjusting the codes and coding until each file had been analysed against the same codes. For audio files, codes were applied by highlighting the relevant section of the audio (Figure 3.3) and linked to the transcript (Figure 3.3). The software has functionality which allows a weighting to be applied to each code. This was used with some of the codes in the site data reports, with weightings assigned to rate the extent to which the highlighted text supported the code. For instance, when coding the responses to the survey question '*was there evidence of poor quality construction*' a code from 1 to 5 was assigned depending on the strength of the evidence of poor quality construction reported by the site engineers. These weightings were reviewed along side each other at the end of the process and calibrated through a comparative judgement exercise, whereby the relevant excerpts were placed in order of their weighting and reviewed against those given a higher or lower weighting.

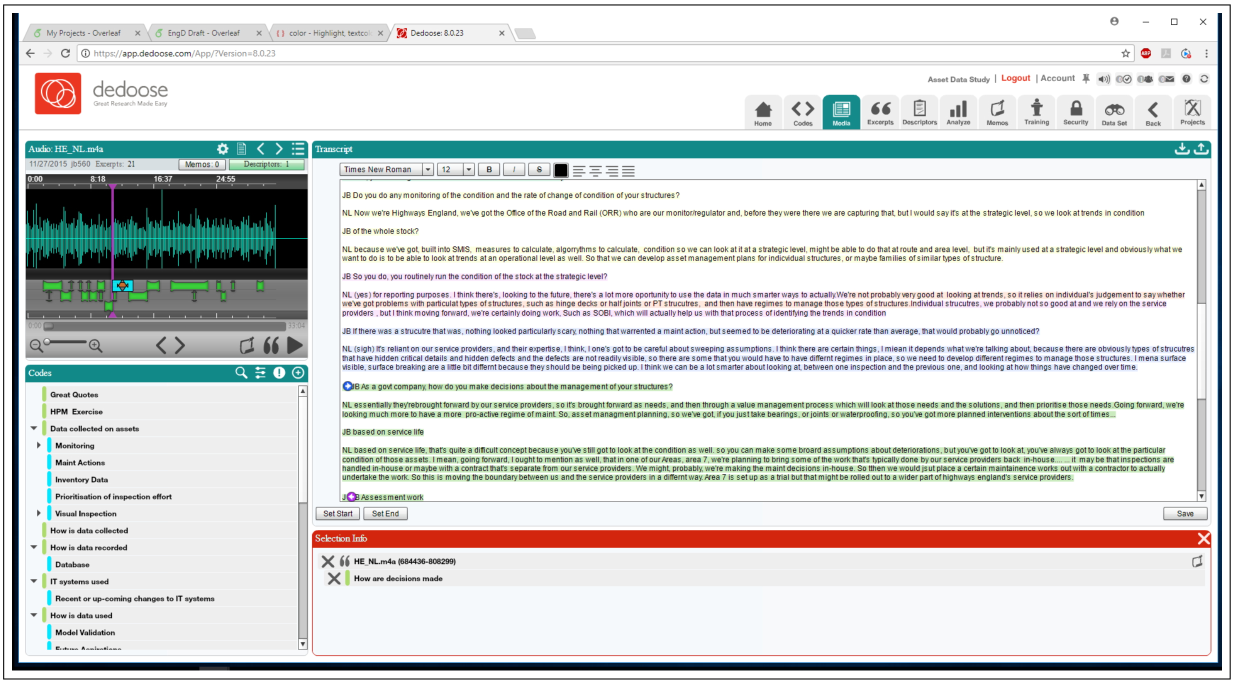

Figure 3.3: Audio coding and transcription interface in Dedoose.com

3.3 Hierarchical process modelling

Complicated processes can be reduced into a series of sub-processes, and sub-sub-processes and so on until each of the sub-processes are simple activities. In this way, a hierarchical tree structure of processes can be built, with sub-processes answering the question *"how do we do this process?"*, and parent processes answering the question *"why do we do this process?"*. This type of modelling by individual '*experts*' has been applied in the literature to model the performance of engineering systems in which there is significant degree of complexity and uncertainty, particularly in civil engineering (e.g., Blockley & Godfrey 2000, Davis & Hall 2003, Hall *et al.* 2004, Blockley *et al.* 2012). However, it is not anticipated that any one '*expert*' would be able to produce a model of the UK's bridge management system encompassing all of its facets because there are a number of different agents within the system, which each have different visibility and perspectives on the whole system. Davis *et al.* (2010) report successful use of group sessions for building Hierarchical Process Models when *"no single person can understand all aspects, issues and variables of such an intricate problem"*. Furthermore, Lane (1992) argues that the approach of individuals building conceptual systems models as '*experts*' can reduce stakeholder trust in the models and chances of making successful interventions. Reviewing the options for building models of the bridge management system, it was therefore considered preferable to hold group modelling sessions with stakeholders from different organisations in the system. However in this case, because of the organisational and spatial distribution of the key stakeholders, it was not viable to convene a meaningful panel to engage in a group modelling exercise. Therefore, the process of group model building was distributed across a series of smaller, often individual, facilitated model building sessions. In this way, individual sessions were held with key actors to produce a model that captures their perspective on the overall system.

3.4 Decision tree learning

3.4.1 The optimal decision tree algorithm

Decision trees can be considered to present a hierarchical series of questions about an object's attributes with the goal of gaining information about the object's likely value of a target attribute. They allow identification and presentation of the most influential categorical factors that affect the outcome of a target attribute. An optimal decision tree would partition the dataset into values of the target variable as well as possible, with the smallest number of questions. The building of optimal decision trees allows categorical datasets to be processed and visualised, either for data mining (presented in this thesis as 'importance dendrograms'), or as a machine learning technique to allow predictions based on a training set of data. Optimal decision trees can be built in a top-down inductive manner, at each tier selecting the 'best' attribute to partition the data by. The choice of test for selecting the 'best' attribute is important in developing a tool that will produce simple trees to classify data. Many tests have been proposed, such as statistical significance testing (Kass, 1980) or information gain (Quinlan, 1986). This work uses the information gain calculated in the same manner as the ID3 machine learning algorithm as described in Quinlan (1986), which uses the concept of information entropy (Shannon, 1948). The technique finds the entropy (a measure of the randomness, or uncertainty) of the whole dataset and then finds the entropy of sub-sets of the data partitioned by the values of the attributes, weighted by their empirical probability. In this way, the information gained by partitioning on a certain attribute can be measured. The algorithm selects the attribute that results in the greatest information gain and then calls the process recursively on each of the sub trees created.

The concept of information entropy was first reported in Shannon (1948) as a method to characterise the uncertainty in a piece of information. Shannon (1948) proposed the use of logarithms because their properties matched the three key properties that he identified as fundamental to his concept. For a set of outcomes, n, from an event each with probabilities $P_1, P_2, \ldots, P_n$ respectively Shannon suggested that a measure of the uncertainty in the outcome, $H(P_1, P_2, \ldots, P_n)$, would have the following properties:

1. "*H should be continuous in the P_i.*
2. *If all the P_i are equal, $P_i = 1/n$, then H should be a monotonic increasing function of n. With equally likely events there is more choice, or uncertainty, when there are more possible events.*
3. *If a choice be broken down into two successive choices, the original H should be the weighted sum of the individual values of H*" (Shannon, 1948).

Shannon (1948) explains that a function that satisfies these criteria has the following format:

$$H = -K \sum_{i=1}^{n} P_i log P_i \tag{3.1}$$

(Shannon, 1948)

Noting that if base 2 is used the information gain is expressed in logical bits, and that the constant K serves only to scale the results, the following expression was proposed:

$$H = -\sum_{i=1}^{n} P_i log_2 P_i \tag{3.2}$$

(Shannon, 1948)

Taking this measure of 'information gain', the categorical attributes of bridges, such as their *'structural form'*, *'articulation'* or *'construction material'* could be compared such that the attribute that provided the most information regarding the target attribute (in this case bridge condition or rate of deterioration) could be identified. This was then repeated for sub-sets of the data for each value of the chosen attribute i.e. if *'Region'* was the attribute that provided the most information, then the data was split into a sub-tree for each individual region and then the process was applied again for the remaining attributes.

3.4.2 Presentation as importance dendrograms

Software tools implementing this process for bridge condition data were developed for this work in the Python 3.x environment to build optimised decision trees from input spreadsheets containing rows of items (in this example bridges), with columns giving the values of different attributes, the last of which being the target attribute. The Newick Tree data structure, implemented in the ETE3 (Huerta-Cepas *et al.*, 2010) library, was used to store, traverse and render the resulting hierarchical data structure. The resulting hierarchical-tree data structures were rendered as 'importance dendrograms' with pie charts on the nodes to display the distribution of the target attribute (e.g. *'Condition'* or *'Change in Condition'*) for the sub-tree below each node. The pie charts were drawn such that the area is inversely proportional to the entropy of the sub-tree, this allows the most informative results to be readily identified by the size of the pie chart. The depth of the trees has been limited, and only nodes representing a minimum number of structures have been drawn to improve the readability of the plots. Importance dendrograms have been generated and presented for the factors affecting the current condition of Highways England's bridge stock, and also for the rate of change in condition of the bridge stock.

3.5 Stochastic modelling

A stochastic process is defined as "*A random process that evolves over time. A stochastic process and a random process often have the same meaning.*" (Gagniuc, 2017). In the context of bridge management, the principal example is the transfer of a component from one condition to another. Where such a stochastic process of transitioning between states is modelled over discrete time (usually time) steps, and the probabilities of transitioning from one state to another (memorylessness) is only a function of the current state, then the process is termed a 'Markov Process', or 'Markov Chain'. Markov chains, or similar processes that do not meet the strict definition of a Markov chain, are a well-established technique in asset management and bridge engineering (e.g. Thompson *et al.* 1998, Enright & Frangopol 1999, Frangopol *et al.* 2001, Sobanjo 2011, Sheils *et al.* 2012, Schraven *et al.* 2013, Rafiq *et al.* 2014). Yianni *et al.* (2017) give a history of the use of implementation of Markovian techniques for bridge asset management. Purely Markovian processes are often characterised by a 'transfer' matrix giving the probabilities of transitioning from each state to the others, given the current state. For example in a process with four states A to D, the transfer matrix would be as follows:

$$T = \begin{pmatrix} p(A|A) & p(B|A) & p(C|A) & p(D|A) \\ p(A|B) & p(B|B) & p(C|B) & p(D|B) \\ p(A|C) & p(B|C) & p(C|C) & p(D|C) \\ p(A|D) & p(B|D) & p(C|D) & p(D|D) \end{pmatrix} \tag{3.3}$$

In a deterioration process, where each state is 'worse' than the previous state, the matrix would be upper triangular, as the probabilities of returning to a 'better' state would be zero. In the simplest form, if the state can only 'decay' to the next state, and this probability is not a function of the current state, then the transition matrix becomes:

$$T = \begin{pmatrix} 1-D & D & 0 & 0 \\ 0 & 1-D & D & 0 \\ 0 & 0 & 1-D & D \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{3.4}$$

where D is the decay rate - the probability of decay to the next state at each time step.

3.5.1 Monte-Carlo analysis

When modelling random processes using probabilistic methods such as Markov chains, the result is expected to be different every time the simulation is run. To recover the statistical variation of the output, the results of a large number of runs (or 'realisations') can be aggregated together. This is known as a Monte-Carlo simulation. The number of simulations should be chosen such that the desired output variables would not vary significantly if the more simulations are run.

Chapter 4

Understanding Current Bridge Management Practice

Aspects of this chapter have been reported in Bennetts et al. *(2016) and Bennetts* et al. *(2019).*

Bennetts J., Vardanega P. J., Taylor C. A. & Denton S. R. (2016) Bridge data - What do we collect and how do we use it? In: *Transforming the Future of Infrastructure through Smarter Information: Proceedings of the International Conference on Smart Infrastructure and Construction, 27-29 June 2016, Cambridge, UK* (Mair R. J., Soga K., Jin Y., Parlikan A. K. & Schooling J. M., eds), ICE Publishing, London, United Kingdom, pp. 531–536

Bennetts J., Vardanega P., Taylor C. A. & Denton S. R. (2019) Survey of the use of data in UK bridge asset management. *Proceedings of the Institution of Civil Engineers - Bridge Engineering, under review*

4.1 Introduction

The ownership of bridge assets in the UK is split based on transport mode, strategic importance, and location. The management of these assets is often further delegated to contractors, with specialist sub-contractors and consultants frequently picking up more complex work, load-rating assessments and renewal designs. The consequence of this is that asset data collection and decision making processes across the bridge stock are highly heterogeneous, with no clear view of current practice available in standards or the literature. This chapter presents a narrative around the management of the UK's bridge structures, focused on the collection and use of bridge condition data as part of a decision making system. The work has been built from a series of semi-structured interviews with key individuals in bridge management organisations around the UK.

Table 4.1: Details of the interviewees' roles and sectors

Ref.	Role	Sector	Scope
C1	Senior Policy Advisor	Highways	Strategic
C2	Structures Manager	Highways	Metropolitan Transport Authority
C3	Structures Manager	Highways	Local
C4	Structures Engineer	Highways	Local
C5	Structures Asset Manager	Rail	Strategic
C6	Structures Manager	Rapid transit	Metropolitan Transport Authority
C7	Regional Structures Specialist	Highways	Strategic
C8	Head of Engineering	Highways	Strategic, Concessionaire
C9	Assistant Head of Engineering	Highways	Strategic, Concessionaire
C10	Researcher	Highways	Local, Heritage
C11	Structures Watchman	Highways	Strategic, Service Provider
C12	Chief Bridge Engineer	Rail	Strategic
C13	Professor	Academia	National
C14	Head of Bridge Engineering	Engineering Consultant	International
C15	Chief Executive Officer	Highways Concessionaire	Strategic
C16	Technical Director	Highways Concessionaire	Strategic
C17	Bridge Specialist	Highways	Strategic

4.2 Methodology

4.2.1 Semi-structured interviews

The research was designed as a cross-sectional series of semi-structured interviews with individuals in UK bridge management. In selecting the participants for such a study, it is important that the respondents are representative of the main population (e.g., Oppenheim 1992). Therefore, the participants interviewed were selected to be representative of the range of agents in the UK bridge management system, including individuals responsible for setting policy in major organisations, as well as those inspecting and making decisions on individual structures. Particular care was taken in ensuring that the all transport modes, levels of authority (i.e. strategic, city region and local authority) and elements of the supply chain were included. In total, 14 interviews were conducted, with 17 participants who collectively have nearly 500 years' experience in the sector. Table 4.1 shows the details of the interviewees' organisational roles and the sectors in which they work. Throughout this chapter, quotations from those interviewed are presented and are referenced using the notation shown in Table 1 (e.g., **C1**) printed in brackets following the quotation.

The interview approach was standardised by using the same interview protocol for each interview, which explored key research questions and areas for enquiry. All interviews were performed by the author, and great care was taken to avoid leading the interview candidates. The research consciously adopted a mixed-methods approach with positivist research questions for some aspects, such as "*what data do you collect on your structures*". A more inductive, Grounded Theory (Glaser & Strauss, 1967), approach was taken for questions such as "*how does your organisation make decisions*". Practice interviews were conducted to refine the interview protocol, interview style and recording. A copy of the interview protocol is included in Appendix B. The interviews were recorded digitally and then analysed by coding against research questions and emerging themes in the audio files (e.g., Saunders *et al.* 2009a). Dedoose.com, a Computer aided qualitative data analysis software (CAQDAS) package, was used to facilitate a thorough and auditable approach. A series of codes (Table 4.2) was set up in the package, which were then applied to relevant sections of the interview audio files, as shown in figure 3.2. The coding schema was developed inductively and updated as the interviews were processed, resulting in an iterative process as already coded files were reviewed and reflected upon as new files were analysed and themes emerged.

4.2.2 Hierarchical Process Modelling

During each interview, the candidates were asked to build Hierarchical Process Models of the bridge management system. See Section 3.3 for further details of Hierarchical Process Modelling. These individual models were then synthesised by the author into one over-arching model which encompasses all of the individual perspectives. The modelling sessions were introduced as part of the

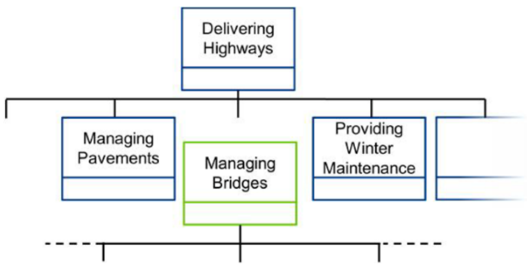

Figure 4.1: Seed Hierarchical Process Model, presented to the candidates in the highways sector

semi-structured interviews, with candidates introduced to an example of a simple Hierarchical Process Models for *'Being a Water plc'* and *'Owning a Dam'* as presented in Blockley *et al.* (2012). The interviewees were then given a 'seed' for a Bridge Management model as shown in Figure 4.1. The intention of the seed was to set the context and scope for a bridge management model, within the organisation and sector that the candidate operated. These seeds were adjusted to reflect the sector and scope of each candidate's role.

Table 4.2: Coding schema applied to the interview data

Ref.	Code
00	**Great Quotes**
1	**Data collected on assets**
1.1	Monitoring
1.1.1	SHM
1.2	Visual Inspection
1.2.1	Risk based inspection intervals
1.2.1	Reliability of visual inspection
1.3	Inventory data
1.4	Maintenance actions
1.5	Prioritisation of inspection effort
2	**How is data collected**
3	**How is data recorded**
3.1	Database
4	**IT systems used**
4.1	Recent or up-coming changes to IT systems
5	**How is data used**
5.1	Identifying need
5.2	Trends in data
5.3	Future aspirations
5.4	Tool for measuring service provider performance
5.5	Audit trail
5.6	Producing condition scores
5.7	Model validation
5.8	Targeting further testing/inspection
5.9	Informing assessment
6	**How are decisions made**
6.1	Judgement
6.2	Deterioration modelling
6.3	Value for money
6.4	Standard maintenance periods/plans
6.5	For assessment work?
6.6	Assumptions on lifespan?
6.7	Prioritisation
6.8	Asset lifecycle planning
6.9	Whole life cost
6.10	Peer Review
6.11	Heuristics
7	**HPM Exercise**

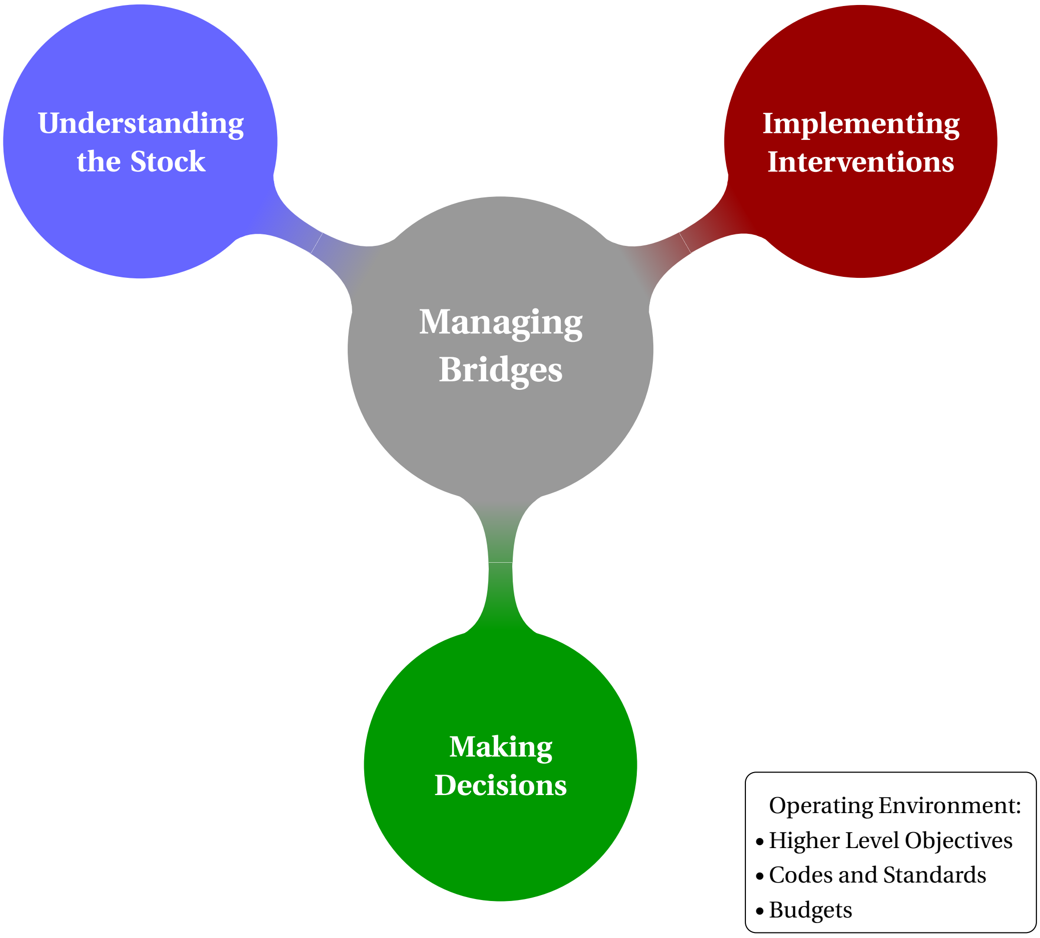

Figure 4.2: High-level model of the Bridge Management system

4.3 Modelling the bridge management process

At the top level, all of the processes identified by candidates could be categorised under three fundamental processes: understanding the stock; making decisions; and implementing interventions. These fundamental processes operate within a framework that is defined by the organisation's higher level objectives, industry codes of practice and standards and is bounded by budgetary constraints. It can be seen that the three identified core processes often follow sequentially, and cyclically, in time and therefore could also be taken to represent a typical Action Research reflect-plan-act-observe-reflect cycle, as per Kemmis *et al.* (1988).

For strategic-level organisations, significant links and interactions were noted between the processes within the bridge management system and the operating environment, with some seeking to control the operating environment by justifying increases to budget, contributing to standards and informing objectives. In effect, these organisations have been able to expand their system boundary and engage in the national socio-political system to improve their position. For some organisations, a significant portion of the interviewed individual's efforts were reported to be dedicated to the

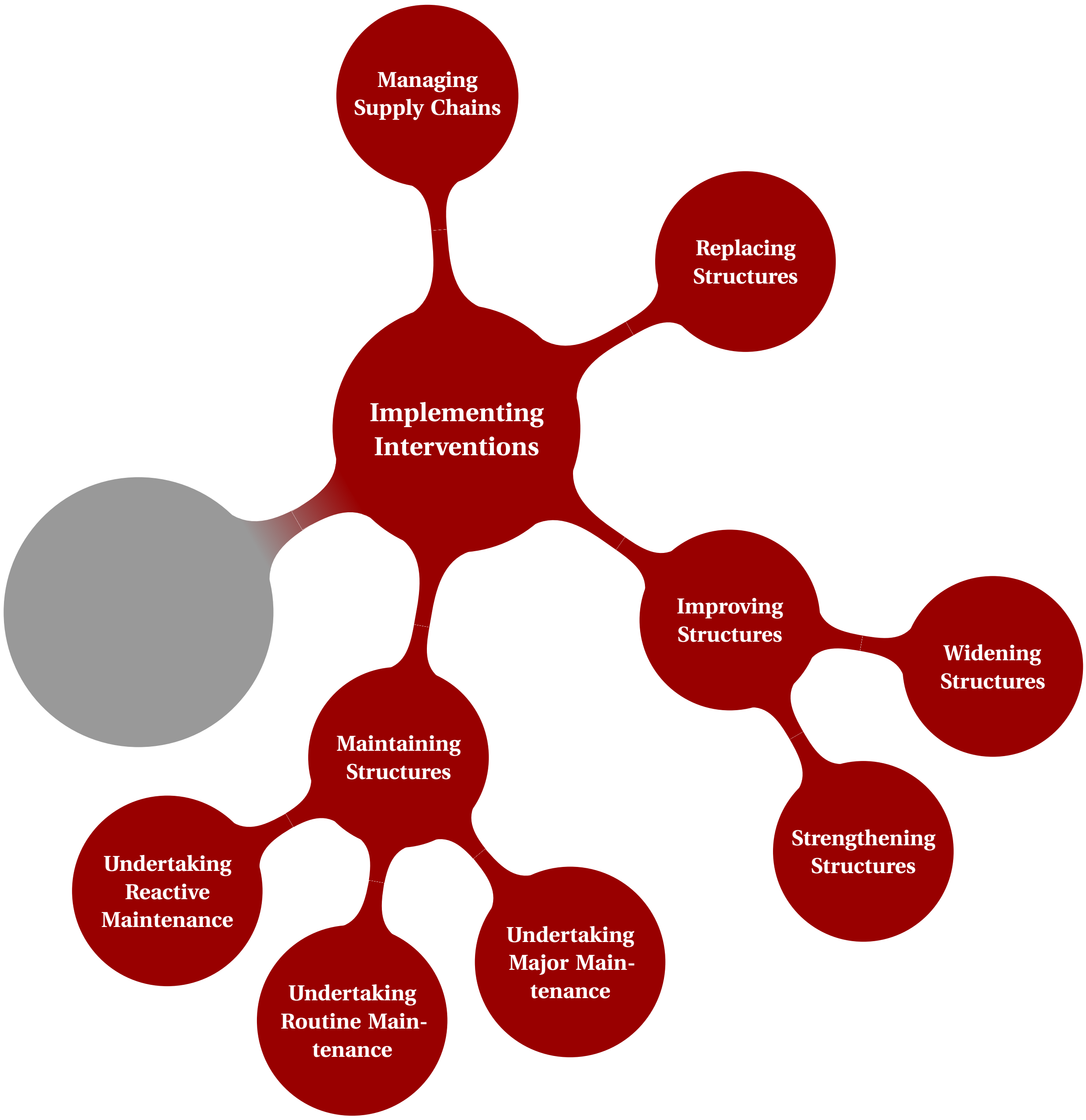

Figure 4.3: Hierarchical Process Model of the *Making Decisions* process within the high-level process of *Managing Bridges*

creation and maintenance of relevant codes and standards, however this has been taken to be activity outside the core process of managing bridges.

4.4 Implementing interventions

Bridge managers have a relatively small number of fundamental intervention options open to them: they can maintain existing bridges to renew their condition, they can improve existing structures to increase their carrying capacity (either in lane width, or load rating), or they can choose to demolish or replace structures at the end of their service lives. Most bridge owners reported programmes of routine maintenance, and systems for reacting quickly to urgent safety-critical issues reported through inspections, user hot-lines or network control centres. Another key activity was reported to be maintaining an engaged and proactive supply chain, which was noted to be crucial to enabling cost effective interventions: "*If you don't get the [implementation of interventions right] everything else will be a waste of time because you need a supply chain that are with you and like you*" (**C15**).

4.5 Understanding the stock

Maintaining a deep and up-to-date understanding of the stock of bridges an organisation is responsible for is crucial to being able to effectively plan activities and expenditure to manage the risks caused by ageing infrastructure, environmental hazards, and accidental events. Maintaining this understanding comprises four key activities: compiling and maintaining an inventory of the structures an organisation is responsible for; monitoring and maintaining records of their condition; maintaining records of their capacity; and managing risks to safety or functionality.

4.5.1 Compiling inventory and recording data

The majority of the interviewees reported that their bridge information is held in dedicated databases which typically hold inventory, inspection and maintenance data. These databases often also hold the results of load-rating assessments and risk assessments such as for scour or road safety. The maturity of these tools varies, with a few organisations relying on spreadsheets for some aspects of their data management, while others have complex integrated IT solutions. Many participants mentioned either newly implemented or imminent IT solutions: "*We're in the process of rolling it [the new system] out … it pulls all those databases together, so we've got one version of truth*" (**C5**). Another interviewee reported on developing a new system: "*Well it's still in its infancy, I mean we've probably been running it for 3 or 4 years now and it's evolved slightly as well … we've now got a refined approach … we'll refine the process as well and keep reviewing it, and it'll become better and better and also we'll have more historical data to be able to verify against as well*" (**C2**).

4.5.2 Visual inspection

Without exception, all of the organisations use visual inspection as their primary source of condition data, and many see it as driving the management of their structures. One participant said: "*Inspections are, really, the foundation for everything we do*" (**C3**). The majority of inspection recording protocols

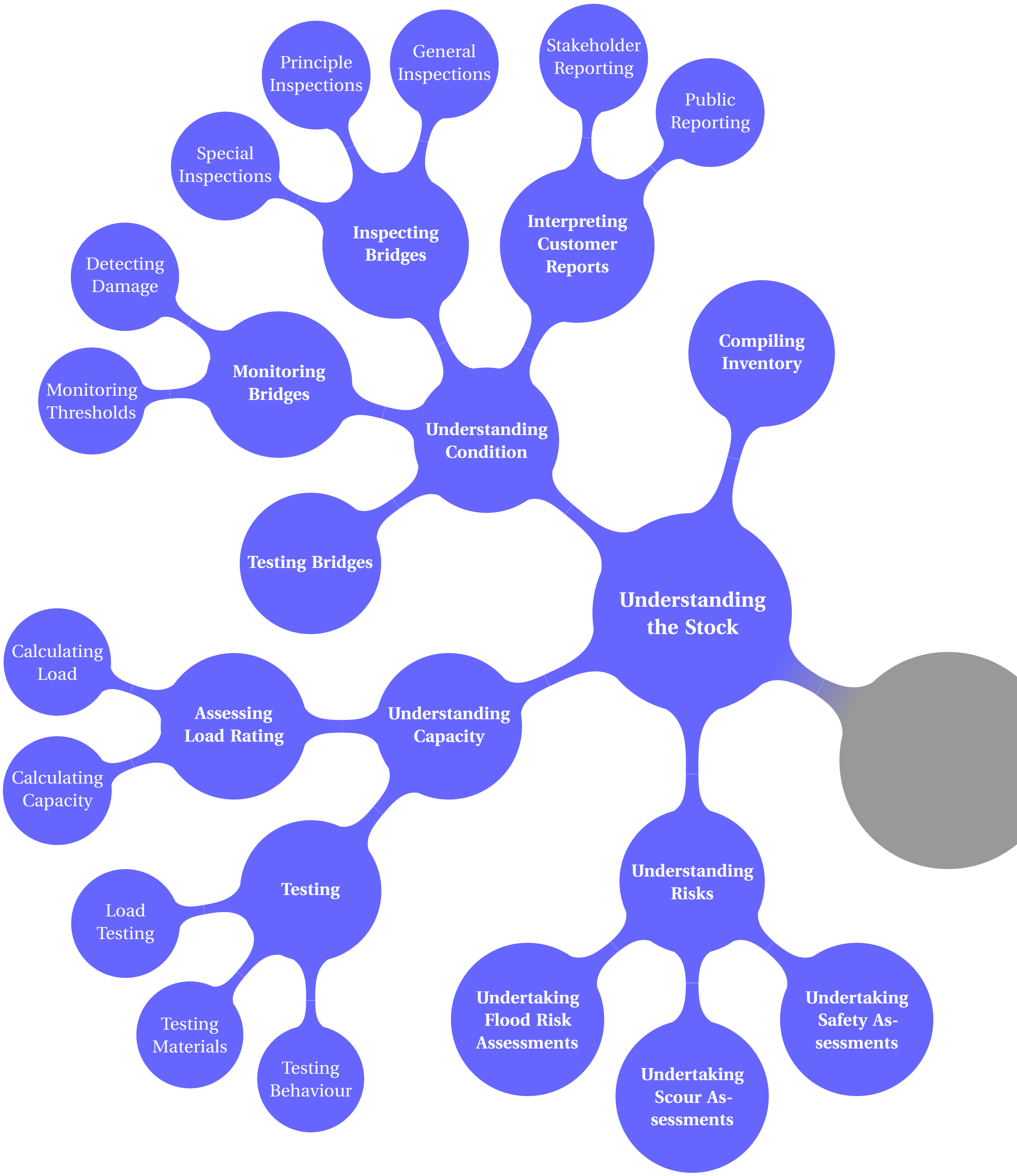

Figure 4.4: Hierarchical Process Model of the *Understanding the Stock* process within the high-level process of *Managing Bridges*

record condition data as the nature, severity and extent of the defects, mostly using the County Surveyors' Society system described in Sterritt & Shetty (2002), or adaptations thereof. The rail sector uses a similar process, but records defect risk in terms of consequence and likelihood. Inspections are typically also used to record maintenance actions, which may be tagged to specific defects and allocated indicative costs: "*We record suggested remedial works, indicative prices, that sort of thing*" (**C4**). Recently, many organisations have begun to extend the inspection intervals for some structures beyond 6 years on a risk basis: "*The cycle is dependent on risk, so if you've got a brand new concrete or weathering steel structure you might want to look at it less frequently*" (**C5**). While one participant questioned the value of the frequent, but superficial General Inspections in current visual inspection programme: "*Take a General Inspection, I half think you're doing it for your own self conscious, I don't think there's much merit in it*" (**C15**). An interesting feature of the rail sector's inspection programme is that it has been aligned with the inspections for assessment required for an 18 year cycle of steady-state load-rating assessments such that "*every 18 years you will get an engineer, doing an examination [whereas otherwise] ... our examiners are generally ex-trades[people]*" (**C5**). Several participants noted the importance of ensuring the reliability of inspection data, for example: "*... subsequently we obviously make the decisions on it, and if you're making it on the basis of unreliable data then that's clearly poor practice*" (**C1**). Evidence for the variability of inspection data was noted, including an unpublished study where inspectors from 5 local authorities were each asked to inspect the same bridge, with marked variations between inspectors. Several respondents reported a lack of confidence in the quality of inspections delivered by their supply chain: "*We are finding the quality of those inspections that we're getting done externally is ... inadequate*" (**C2**). Consequently, some respondents reported that they are looking at changing the delivery of their inspection programmes: "*It may be that inspections are handled in-house or maybe with a contract that's separate from our [highway maintenance] service providers*" (**C1**).

Looking to the future, the participants disagreed in the role of visual inspections to maintain our understanding of bridge condition. Some saw that there would always be a role for visual inspections, perhaps augmented with technology: "*... visual inspection will still form the basis of most inspections, quite rightly, with competent trained individuals, but using photographs and video to get an objective image which is then automatically overlain on the existing model, and tracks changes with time*" (**C13**). Whereas others foresee a time when a combination of technologies to monitor a bridge's condition and predict its future: "*Inspection of bridges, how long are you going to do that for? A year? Maybe two? You don't need to do that any more. You absolutely don't need to do that any more. You think you do, because that's what you're used to but, with the technology that's coming on at the moment and the way you can actually pinpoint how a bridge is operating, it's a small step from a piece of infrastructure, to wiring it up, to gathering the data, to analysing it and the only time you will need to do a visual inspection is when you have been told by the computer that there is a problem with this bridge*" (**C15**).

4.5.3 Monitoring inspections

If an element of a structure is deemed to require a higher frequency or fidelity of data collection than the routine visual inspection process, most of the organisations interviewed would implement a programme of monitoring inspections. The inspection periods would be reviewed depending on the severity of the defect, on-going deterioration and the importance of the element: "*It's a balance between keeping everything safe, and keeping an eye on everything and working within the resources we're given*" (**C3**).

4.5.4 Structural health monitoring

"*The vision we talk about is a ubiquitous world like cars where it tells us everything about it. I think we've got quite a long way to get to that, but it should be an ambition - whether it is viable and economic is still an interesting one*" (**C13**). The deployment of structural health monitoring systems was generally reported to be limited to specific structures with particularly serious defects which are critical to the network: "*We have specific monitoring, so if we've got a specific problem we're concerned about and we want to gain information about it then we will . . . have targeted monitoring, [that] definitely will help with what we need to do . . . we're talking about a handful of cases*" (**C2**). Another interviewee similarly reported that: "*We have, probably a dozen sites where we have real-time monitoring. They're the stuff we're really worried about . . . it's not very often, but we do do-it*" (**C5**), while another said that, if they were to deploy SHM, "*it would be, very much, targeted*" (**C1**). One participant noted the reassurance monitoring a structure had given them to keep a structure in service: "*Given the choice of doing it again, or not doing it, I would definitely implement it again . . . for the piece of mind, and really we needed it for BD 79 - we needed some justification to keep the road open*" (**C16**). Some interviewees responded that in terms of monitoring systems they have "*none at the moment . . . not any remote monitoring*" (**C11**). The exception to this is for asset managers responsible for large and strategically important structures: "*Where do we start? We're monitoring wire breaks . . . there's wind speed for bridge closure . . . there's the weigh-in-motion system . . .* " (**C8**, **C9**). Some of the interviewees indicated their interest in potentially deploying structural health monitoring in the future: "*I am aware of . . . remote monitoring as well*" (**C3**), while another interviewee stated that: "*We probably don't do as much as we should*" (**C2**). Others - when asked if there is monitoring they would like to do, but currently do not - noted that the condition of their structures does not currently warrant the use of monitoring systems: "*We've not really got anything that is of a serious concern, to say I really want that minute-by-minute*" (**C6**). Others noted the cost of monitoring systems as a deterrent: "*Part of it would be cost, so, can we justify putting it in?*" (**C2**), and looked forward to lower-cost commoditised sensors: "*Wouldn't it be good to have a 21st Century Inspectors Toolbox, . . . a box of various cheap widely available and easy to connect sensors?*" (**C12**). It was also noted that "*the use of the data's the key thing, and what I found is when it came to the assessment stage, the use of this data was very weak*" (**C13**) and that in specifying systems, managers need to ask themselves "*what is this monitoring really going to tell you?*" (**C5**).

Several participants anticipated an increase in the use of image processing techniques to augment and replace more traditional monitoring and inspection methods: "*Without question augmented reality and virtual reality is going to be an absolute game changer. Computer vision is a no-brainer*" (**C13**). One participant noted positive results of replacing traditional strain gauges with digital image correlation (DIC): "*We've been doing a combination of strain gauging and digital image correlation to take multiple strain fields over difficult to access areas such as over the railway line. That's a technique we're using more and more, actually* " (**C14**).

4.5.5 Load-rating assessments

Several candidates recognised the link between understanding the condition of their structures and assessing their capacity: "*There's interaction between the two sides, so it may be that an assessment triggers an additional inspection. Examination may trigger assessment [which is] more likely than assessment triggering an examination*" (**C5**) and one suggested change in condition can trigger a reassessment of load-rating: "*So it's as things change, or we're aware of some deterioration that effects the assessment, then we look at reassessing*" (**C3**). Monitoring data may also be used to verify structural analysis: "*As part of the assessment process, we do use strain gauges or whatever, so we can back analyse*" (**C5**).

4.6 Uses of bridge asset data

Several participants linked the data that is collected and recorded and its use to inform management decisions: "*[The database] is just a repository for data, and perhaps some information, the knowledge is how you use it, and the wisdom is implementing that*" (**C1**). The use of the data varies across the organisations interviewed, however, generally it was possible to categorise it into: identification of need; informing assessment; analysis of trends; provision of an audit trail or use as a contractual tool.

4.6.1 Identifying and prioritising need

Identifying the need for maintenance interventions is the most common use for bridge condition data: "*So we get a great big long list [element by element, across all structures], so we can look at that and say those are the sorts of things we need to be looking at, and that's a first pass*" (**C2**). One interviewee reported that they rely on contractors to identify renewals: "*A lot of it relies on our service providers . . . to identify need*" (**C1**). Monitoring data too is used to identify needs and target interventions to resolve them: "*Take the example of acoustic emissions - we collate the data so we know where the highest instances of wire breaks is . . . if we did get a cluster of wire breaks, then obviously when we went in to do our next intrusive inspection, then that [data] would feed into the selection of the panels for the intrusive inspection*" (**C9**).

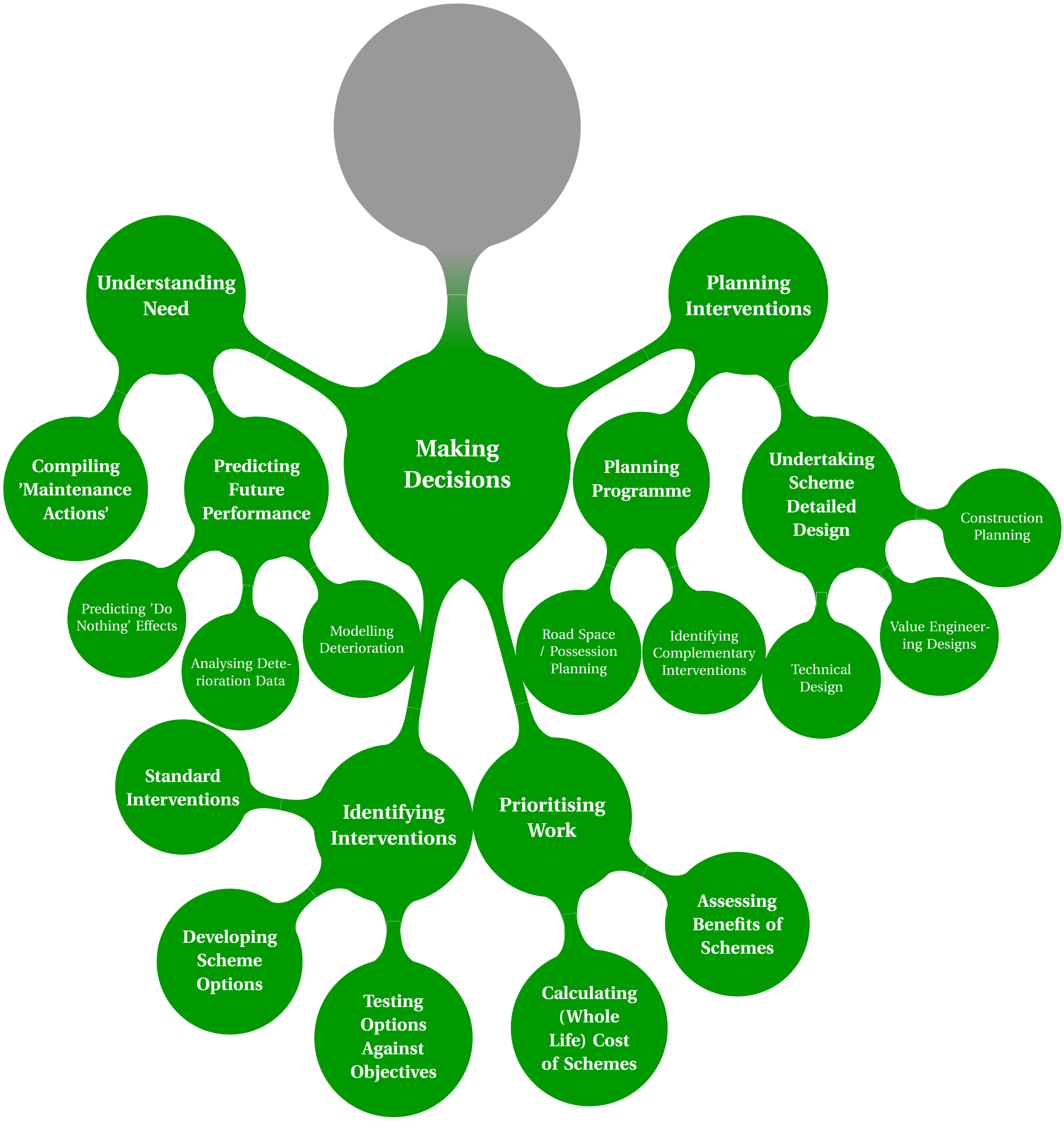

Figure 4.5: Hierarchical Process Model of the *Making Decisions* process within the high-level process of *Managing Bridges*

4.6.2 Analysing trends

All of the owners had some overview of the trends in their stock's condition with time, and some monitor trends in sub-populations of their stocks: "*We look at trends at a family level, so for this family of structures we have the probability of a structure falling from one condition grade to the next*" (**C12**). There was recognition that analysing trends is an opportunity for future development: "*So we look at trends in condition ... but it's mainly used at a strategic level and obviously what we want to do is to be able to look at trends at an operational level as well ... looking to the future, there's a lot more opportunity to use the data in much smarter ways ... we're not probably very good at looking at trends, so it relies on individual's judgement to say whether we've got problems with particular types of structures*" (**C1**).

4.6.3 Maintaining an audit trail

One important use of data is to provide an evidence base to justify decisions to do work and what work to do: "*We have a finite resource; it's about justifying where's the best place to spend it*" (**C2**). Another organisation noted that it can be just as important to justify when work is not done: "*That priority score also helps us defend not doing something to politicians or the public*" (**C3**).

4.6.4 As a contractual tool

The management decisions for some structures are delegated from the asset owner to contractors who are given responsibility for maintaining the asset for a number of years. It is in the asset owners' interests to put measures in place to ensure that good decisions are made for the long-term performance of the structures, rather than short-term profit of the contractor. Two of the organisations interviewed noted contractual terms related to the condition of the assets: "*We have to hand it back in a condition which allows it to be operated for the remainder of its design life*" (**C9**) and one interviewee noted contractual terms that specifically use condition data "*on a fixed date at the end of the contract they have to hand back all structures with a BCI score of 90 or above*" (**C6**). A third organisation noted interest in using condition scores as a contractual tool for measuring service provider performance in the future.

4.7 Decision making

While the systems and processes by which management decisions are taken were found to vary considerably across the organisations, it was possible to identify some common themes.

4.7.1 Prioritisation processes

All of the participants stated that they undertake some sort of prioritisation process to decide what work to do and when. For some organisations, this is quite a simple process: "*The priority is often* *very simple ... we've a high, medium or low priority*" (**C5**), whilst other organisations have more quantitative approaches: "*We've got our own priority scoring system ... Which relates to the importance of the element, the severity of the defect, the size of the structure in terms of deck area, and cost*" (**C4**). One interviewee set out their prioritisation process as follows: "*We have an inspection programme, which highlights defects in structures, which generates what we call a risk score ... those highest risk scores go forward to a renewals programme and what we then try and do is, through Value Management, prioritise those renewals*" (**C7**). It is worth noting that, while at least two organisations referred to a "Value Management" process, the mechanics of these processes had some significant differences, particularly in whether they are used to prioritise need, appraise solution options, or prioritise schemes put forward as the best solution to a need. The incorporation of costs into the processes also had significant differences, with some calculating a ratio of risk reduction per pound: "*Effectively, we start off with the three risk categories and then we prioritise on that, and then we ... put the costs against each of those items there, and then we get a value ratio*" (**C2**). Others calculate the ratio of future anticipated savings in whole life cost over immediate cost and then combine that with risk scores. Some individuals reported processes that did not appear to consider cost. While some of the owners had an aspiration for computer systems to combine deterioration modelling and condition monitoring to automatically produce a prioritised maintenance plan, there was scepticism as to whether it's possible at stock level with current technology maturity: "*I don't believe we've got a level of sophistication within that arena to begin to determine what your prioritised programme of interventions are.*" (**C15**). However, such systems were reported to be in place for one flagship project on an individual structure: "*They tend to be slightly bespoke, but there are decision support tools stuck to certain structures. ... the decision support tool [for one strategically important structure] looks at extrapolated condition as one thing, but it's only one of many factors. Other important things are the consequence of loss of an asset, the Traffic Management requirements and the benefits of combining with other work. The deterioration curves are used initially to get the initial plan, but then you should get the data to update it ... of course if you've got data on corrosion, carbonation, cracking/spalling and you've got a couple of snapshots in time you can fit deterioration curves and then update them with actual data. Again, this is in pockets, I'm not pretending we're doing this across the board*" (**C14**).

4.7.2 Lifecycle planning

Many of the interviewees consider the overall lifecycle of their assets. This may include deterioration modelling and whole life costing to inform planned preventative maintenance "*[The system] tries to predict the condition of different elements over the next 30/40 years, which gives us an indication of ... we don't have to do that now, we can do that in 5 years' time etcetera*" (**C4**). One of the organisations had the capability to review the costs and effects of different maintenance strategies for their whole asset stock: "*The whole life costing's based on our lifecycle plans ... in terms of putting the programme together as a whole ... we will also do an absolute minimum scenario, see what does that look like, we'll run an optimised programme, what does that look like*" (**C2**). Other interviewees noted frustrations in attempts to adopt whole life costing approaches: "*We've tried in the past ... we used to have a system [which] I never got on with because it always came up with the same answer in my mind which was, 'the cheapest option today is the best'*" (**C5**).

4.7.3 Standard asset operating policies

One approach to managing structures is to set out standard operating policies for different kinds of assets and components. For example, prescribing that bearings are to be greased every x years, and then eventually replaced after y years. Alternatively, policy could set out standard interventions for common defects, and specify condition trigger levels for different intervention types. The benefits of this are a unified approach across an asset stock, and a move to planed preventative maintenance, with low down-time, rather than reactive maintenance. These approaches were noted to be taken by some organisations: "*So those maintenance manuals will have 'this area once every x years' so there's a rolling programme you take out every year*" (**C8**). In the rail sector, it was reported that standard interventions are used as "*a starter for ten*" (**C5**). However, while noting an intention to develop policy in this area, some participants were more cautious about such approaches: "*You can make some broad assumptions about deteriorations but you've always got to look at the particular condition of those assets*" (**C1**).

4.7.4 Engineering judgement

All eleven individuals interviewed stressed the continued importance of engineering judgement in making bridge management decisions: "*Engineering judgement still rules the day*" (**C5**). The two larger, strategic, organisations interviewed both mentioned peer review panels as key to their decision making processes: "*We have a peer review process to evaluate decisions ... where I have to pitch to my peers*" (**C5**). A contractor reported discussing the work to be done with the client: "*The list I produce gets discussed at the monthly meetings, so it's pretty much pencilled in at that point which [schemes] are going to be focused on*" (**C11**).

4.8 Concluding remarks

The majority of organisations represented in this survey currently use a programme of visual inspections as their primary source of bridge condition data. The deployment of SHM systems is limited, except in targeted cases where there is a clearly articulated use for the data. Collected bridge condition data is used to inform decisions and, although this paper draws on a limited sample of stakeholder and practitioner views, the study does tend to confirm the perceived heterogeneity of approaches to the management of bridges, particularly in the decision making process.

This study has acted as an extension of the literature review (chapter 2) and grounds the promise of technological advances in the reality of day-to-day practice. It also identifies the research needs of the bridge management community in the UK. Given the on-going reliance on visual inspection data by bridge managers and the concerns about it's quality (e.g. Moore *et al.* 2001a), it is important to understand the reliability of the data that is collected in the UK - this is further investigated in chapter 6. It is then important to understand the value that can be derived from the data that is collected (explored in chapter 7), the needs of stakeholders in decision making processes (chapter 5) and the performance of different decision making strategies when applied to a large stock of bridges (chapter 9).

Chapter 5

Understanding Stakeholder Needs in Asset Decision Making Systems

This chapter is based on work reported in Bennetts (2016).

Bennetts J. (2016) *Support for Revised Project Prioritisation Process for Renewals Schemes, Part 2: Sub Task 4 - Scoping Study. Technical report*, WSP | Parsons Brinckerhoff, on behalf of Highways England

5.1 Introduction

While many authors characterise asset decision making as a mathematical problem (e.g Enright & Frangopol 1999, Sloth *et al.* 2002, Neves & Frangopol 2005, Neves *et al.* 2006, Sobanjo 2011, Rafiq *et al.* 2014), where the outcomes can be 'optimised' against an objective function (e.g. Robert *et al.* 2003), in practice asset decision making can involve many decisions taken by individuals, or agreed between stakeholders. Rather than a clean mathematical formulation, the processes by which these processes are made can be framed by the 'softer' considerations of organisational politics, engineering judgement and human factors. If the needs of these stakeholders are not considered in designing decision making processes, there is a risk that stakeholders' valuable contributions are missed and they may engage in behaviours such as '*decision-based evidence-making*' to bend the systems to the decisions they have already made (Tingling & Brydon, 2010).

To develop an understanding of the views and behaviours of stakeholders in an asset decision making system, this chapter covers a case study into the issues concerning real-world asset decision making processes which are implemented at national scale by a strategic infrastructure owner. The case relates to a review by Highways England of their asset renewals decision process and support tools. The perspectives of a cross-section of stakeholders in Highways England's Value Management system were collected through questionnaires and workshops, with a total of 51 Stakeholders and 7 workshops. Stakeholder views were recorded for the current implementation of Highways England's asset decision making process, Value Management (VM), along with desirable attributes for future generations of the process. The results from the questionnaires and the workshops are presented and discussed. The conclusions are presented as a set of recommendations for future bridge asset management processes which, while developed with a Highways England case study, are of relevance to any asset management organisation.

5.2 Background

Highways England uses a process known as Value Management to identify and prioritise maintenance renewal and improvement schemes on its network (See Section 2.6). Maintenance needs are identified by the teams responsible for managing 'Areas' of the network (often third-party contractors) and are put forward in a bid for funding from Highways England as renewal 'schemes'. Under the Value Management process, each proposed renewals scheme is assessed based on a scoring matrix/framework under three main criteria, namely: Value for Money (VfM), Safety and Sustainability. These three criteria are then weighted according to their relative importance.

Table 5.1: Components of the Value for Money Score. (Adapted from Annex D of Highways England's Portfolio Control Framework (Highways Agency, 2014a))

Category	Description	Weighting
VfM	Assesses value for money using an Economic Indicator (EI) calculation. The EI is a Benefit Cost Ratio that compares the whole life cost of the 'Do Something' option compared to the 'Do Minimum' option.	50%
Safety	Assesses the extent to which the defects within a scheme pose a risk to the safety of road users (and adjoining properties in the event of flooding) and how well the proposed works address this risk.	30%
Sustainability	Assesses the likely impact that the proposed scheme will have on the environment, society and economy.	20%

The same overall process is used for all highway asset types, ranging from 'technology' items such as information signs, to lighting columns and structures such as bridges and retaining walls. The assessment and scoring of each category is based on consideration of a number of elements that vary according to each asset type. Each category is given a weighted score out of 100. These are added together to give a total VM score for each scheme that is used to assist with prioritisation.

Value for money (VfM) is assessed using an Economic Indicator (EI) calculation that is based on minimising whole life costs over a 60 year assessment period. A 'Do Minimum' Option (defined as the must-do activities required to keep the asset safe for 1 year) is compared to a 'Do Something' Option that addresses identified needs at minimum whole life cost.

Dedicated analysis tools are adopted by Highways England to provide data to support this assessment: SWEEP (Software for the Whole life Economic Evaluation of Pavements) is used for pavements (note that in highway engineering 'pavements' refers to all road surfacing, and not just footways); and PEAT (Project Economic Appraisal Tool) for all other assets. These tools are applied for all schemes over £100k, and simplified processes exist for schemes under £100k.

PEAT contains a database of common 'treatments' that could be applied to assets in a maintenance intervention, with indicative costs. For each proposed scheme, a 60 year programme of future works would be developed and compared against a 'do nothing' alternative. The selection of intervention types and timings in PEAT is down to the enjeering judgement of the individual using the tool, and no data or guidance is available. SWEEP is a more complex tool than PEAT and uses in-built deterioration modelling to identify future maintenance treatments. Both PEAT and SWEEP model direct costs (including preliminaries, traffic management and works), but do not include any indirect costs to the road users, local communities or businesses.

The following limitations with the current generation of the VM process have been anecdotally reported by stakeholders to the team responsible for the process within Highways England:

- The VM scoring criteria may not be aligned with Highways England Performance Indicators (for example, pavement renewal alignment to noise important areas).
- The current procedures are resource intensive and do not represent efficient, scalable methods for an expanding programme.
- VfM whole life cost assessment is asset specific and based on direct work costs. It is driven by asset condition, prioritising life expired assets.

5.3 Methodology

5.3.1 Introduction

To record the perspectives of a cross-section of stakeholders in the Value Management process, a study was designed that included the collection of views through questionnaires and series of half-day workshops with stakeholders in the current process.

5.3.2 Stakeholder selection

Stakeholders were chosen to be representative of the various roles that use or maintain an interest in the Value Management process within Highways England and its Service Providers. A cross section of relevant stakeholders involved in the VM process was identified to participate in this scoping study. These included representatives from:

- Highways England - Network Delivery Directorate (NDD), Professional and Technical Solutions (PTS), and Regional Area teams.

Table 5.2: Details of the stakeholder workshops

Workshop	Location	Date
W1	London	03/11/2015 AM
W2	London	03/11/2015 PM
W3	Birmingham	05/11/2015 AM
W4	Birmingham	05/11/2015 PM
W5	Bristol	11/11/2015 AM
W6	Bristol	11/11/2015 PM
W7	Manchester	12/11/2015 AM

- Area Service Providers (contractors)
- Design Build Finance and Operate (DBFO) Contractors

The full list of the stakeholders consulted and their areas of responsibility has not been reported to prevent individuals' comments being attributable. Instead, comments are attributed to one of the seven workshops (e.g. **W7**). A summary of the workshop locations and dates is presented in Table 5.2.

5.3.3 Stakeholder questionnaires

In order to collect the views of selected stakeholders on the Value Management system and potential future development or replacement by alternative systems, stakeholders were invited to complete a questionnaire. The questionnaire was split into two sections: a quantitative section, and a set of open questions. In the quantitative section statements regarding the current Value Management process, and the desirable characteristics of a future Renewal Projects Prioritisation Process were presented and respondents were asked to score their agreement with the presented statements on a Likert scale from 1-9. Where possible, the wording of the statements was chosen to directly mirror text in existing VM documents, the Portfolio Control Framework (Highways Agency, 2014a) and the Road Investment Strategy (Highways Agency, 2014b). Respondents were also given opportunity to comment alongside the statements. The second section was designed to allow stakeholders to respond to a series of open questions covering the current and future VM processes. A blank questionnaire is included in Appendix C.1. In total, 36 completed questionnaires were received; a summary of the results is included in Appendix C.2.

5.3.4 Stakeholder workshops

In order to stimulate discussion and capture the views of the wide range of users and other stakeholders to the Value Management process, a series of 7 half-day workshops was planned. The format of these workshops was set out as follows:

- Introduction and history of the current Value Management process, and the need for a review.

- Review of salient results from the questionnaires.
- Discussion and post-it exercises to explore the performance and benefits of the current process; purpose and objectives of a new system; links to asset management; factors in prioritisation and scoring; and barriers to change.
- Collaborative elicitation of consensus statements on the main issues to be discussed.

A dynamic approach was taken to the facilitation of the workshop sessions, allowing the groups to explore areas of interest. The format also evolved over the course of the workshops to focus on areas of interest and themes that had emerged from earlier workshops. The initial, exploratory, sessions of the workshops were conducted with a mixture of post-it sessions and facilitated discussion. In the post-iIt sessions, participants were asked to write down their responses to research questions such as "what are the benefits of the current VM process?" on post-it notes; they were then asked to discuss their responses with the group. The responses and ensuing discussions were minuted by the project team. Following the discussion and post-it sessions of the workshops, participants were asked to agree statements relating to the areas discussed. These statements were put up on the projector and edited, including caveats where necessary, until all of the participants in the workshop accepted them. These consensus statements are recorded in Appendix C.4 for each workshop, with the appropriate themes referenced for each statement. A total of 7 workshops were run, with 51 participants.

5.3.5 Analysis methods

The numerical questionnaire data has been processed to show the average agreement with each statement and strength of consistency between the respondents.

The qualitative data has been categorised into themes and the relevant excerpts from transcripts, survey responses and workshop consensus statements have been used to build narratives around each of these themes, which are presented in section 5.4 below. The themes used to categorise the data were based both on the initial research questions and emergent themes arising from the survey and workshop responses; the themes are presented in Appendix C.3. Computer Aided Qualitative Date Analysis Software (CAQDAS) by Dedoose Ltd was used to assist in analysing the qualitative data (Section 3.2).

5.4 Results and analysis

The responses to the workshop sessions and questionnaires are presented in the Appendices as follows:

- Appendix C.2 - Questionnaire Results Summary
- Appendix C.4 - Workshop Consensus Statements, tagged with themes

A narrative has been built around the responses under the following themes: the benefits of the current VM process; the issues with the current VM process; the desirable characteristics of future asset decision processes. Any future recommendations are referenced back to the original discussions (**R1**). Quotations from workshop notes and consensus statements are referenced as, e.g (**W1**).

5.4.1 Perceived benefits of the current decision making process

When asked, stakeholders noted that the current process is beneficial to Highways England. In particular the following benefits were noted:

Getting the *"right solution"* The current Value Management process is seen as beneficial in ensuring that Highways England gets "*the right solution, for the right cost, at the right time*" (**W5**). The current structure and phases of the process assist in achieving the right outcomes.

Workshops VM workshops provide a good forum to get people together to discuss asset needs, technical and commercial issues. It is recommended that any future process includes a similar workshop format (**R1**).

Technical review The technical input during Value Management and during workshops is a strongly valued aspect of the current process. Participants also emphasised the benefit in having technical workshops prior to any detailed design work (**R1**).

Commercial review It was noted that the VM process provides an important function in allowing Highways England operational team and technical specialists to challenge Service Providers (third party contractors) and gain oversight and feedback to ensure that the money fits the need (**W7**).

Audit trail The creation of an audit trail is seen as an important aspect of the current VM process which should be retained (**R2**). For example, Workshop 5 agreed that "*VM is important in providing an audit trail for decisions, through minutes of VM workshops and SAR forms*" (**W5**).

Scoring/Prioritisation Stakeholders reported that the scoring process within the current VM process is useful as an indicator of the relative priority of schemes (**W5**). Scoring is also used to compare between different solutions to a need.

National consistency Achieving a consistent approach across the country was seen as key benefit of the current process, for example Workshop 3 agreed that one of the benefits of VM is a "*consistent approach across [the] country*" (**W3**).

5.4.2 Issues with the current decision making process

While noting the benefits of the current Value Management process, several issues with the current process and its implementation were reported by participants in the study:

Effectiveness and outcomes When asked whether they agree with the statement "The current Value Management Process achieves value for money", the questionnaire respondents consistently responded neutrally with an average of 4.94 on the 1 to 9 scale. This suggests that the current process is not perceived as being effective in meeting one of its primary objectives. There were concerns that schemes which fit with national policy do not score well under the current process. Some respondents stated that the process is "*not fit for purpose*" (**W6**), and that it is "*just ticking the box*" (**W7**) for decisions that are already made through engineering judgement. There were several criticisms that the current process confuses the needs and solutions phases. Many participants identified several distinct decision phases which the current VM process is attempting to address, including needs identification, value engineering of solutions and prioritisation of schemes.

Efficiency The current VM process is seen by many stakeholders as inefficient (**W7**). When asked whether they agree with the statement "*The current Value Management process is efficient with staff time*" the survey respondents consistently responded negatively with an average of 3.1 on the 1 to 9 scale. Of particular note is the lack of scaleability in the current process - several participants noted that the same level of evidence can be required for a small scheme as for a major renewal. Anecdotally, the cost of surveys and going through the VM process can be a significant portion of the scheme cost (**W6**, **W5**), and is perceived as poor value for money. Others noted that the detail level of the decision tools needs to be appropriate to the design stage (**R3**,**R4**).

Alignment with Highways England's high level objectives A repeated theme across the workshops and questionnaire respondents was the perception that the Value Management process does not align with Highways England's high level objectives as set out in the Road Investment Strategy (Highways Agency, 2014b) and major initiatives such as Fence-to-Fence. Participants reported that the prioritisation under the current VM system can directly contradict Highways England's objectives (**W5**), for example technology schemes which align with the "*informed customer*" objective are reported to generate low VM scores (**W6**). The scores for sustainability, another key objective, were said to be inadequate (**W6**). Many respondents noted issues with applying fence-to-fence principles within the current VM process, as there is no mechanism for recognising the benefits of delivering multiple schemes together (**R5**).

Implementation in tools and processes The implementation of the current processes in software tools was cited as being "*clunky*" (**W5**), with some respondents saying that there was too much reliance on "*turning the handle to get a number*" (**W5**). The ease of use of current software tools, PEAT and SWEEP, was criticised (**W1**, **W2**, **W6**). IT issues with tools were also a commonly reported issue (**W7**). Many respondents noted that the current tools have not been updated to reflect changes in the organisation, and that as a result they can feel disjointed (**W5**). There were some frustrations regarding the lack of flexibility in the system to allow for non-standard cases; many stakeholders expressed a desire for the system to allow for engineering judgement (**W1**, **W2**, **W5** & **W6**).

Scoring Issues with the current VM scoring process were a common theme across the workshops. Stakeholders reported issues where the derived scores do not appear to align with policy, or where important factors are not considered. Particularly, the inclusion of user costs (**W1**, **W2** & **W4**) and road-worker safety (**W4** & **W5**) were regularly mentioned. A particular issue was a concern that the current scoring processes do not generate scores that can be usefully compared across asset types (**W7**). Many participants reported that these issues meant that, while useful as an indication (**W5**), the scores cannot be used to prioritise schemes (**W6** & **W7**). In contrast, workshop two agreed that there is "*real danger*" in not prioritising schemes based on scores (**W2**).

Required input information The cost of gathering the required information to promote a scheme was discussed as an issue, particularly for small schemes (**W6**). There is a need to ensure that the cost and value of surveys and preliminary work are understood and that this work is proportionate to the scheme cost (**R3**).

Value for money Many of the workshop participants expressed the view that the current process does not achieve value for money, and that aspects of the process do not conform to the British Standard for lifecycle costing (BSI, 2008). The differences between asset lifetimes and maturity of lifecycle planning tools were cited as issues in applying a consistent process across assets. Some participants noted that a lack of funding and a focus on completing all 'do minimum' activities, rather than investing in preventative maintenance schemes, prevents the organisation from achieving value for money (**W4** & **W5**).

Contractual issues Several contractual issues were identified, particularly with Asset Support Contracts (**W1**, **W2** & **W6**). It was noted by several participants that the contract can incentivise certain behaviours from service providers, such as extension or splitting of schemes to suit commercial interests, rather than asset needs. Some participants highlighted the conflict between lump sum routine maintenance activities, and renewals projects, reporting that schemes are brought to Value Management which should be covered in the lump sum. Concerns were also raised by Highways England stakeholders that they do not currently have a full visibility of asset needs, as only the needs relevant to schemes which will be profitable to the service provider will be promoted to Value Management (**W5**).

5.4.3 Desirable characteristics of asset decision making processes

Position of Value Management in project delivery The position of the Value Management process within project delivery was discussed in all of the workshop sessions. While there was no overwhelming consensus as to which stage the process should address, several distinct stages were consistently identified:

- Identification of need.
- Choice of best solution to a given need.
- Value engineering of a solution.
- Prioritisation of schemes to fit budget.
- Production of a programme of works which fits Highways England's Strategy.

Some participants noted that the project delivery process is more cyclical (**W5** & **W7**) than shown in the Portfolio Control Framework (PCF) (Highways Agency, 2014a), with VM considered multiple times as a scheme is developed.

Many stakeholders highlighted a need for "*a consistent method of identifying need*" (**W5**), with some suggesting a risk-based system. It was noted that at least one service provider uses a risk-based needs identification system internally.

The differences between renewals and improvements were frequently highlighted by stakeholders, with a suggestion that it may make sense to have separate Value Management processes (**W6**).

Objectives of a new system During the workshops, participants were asked to discuss and agree what the objectives of a new VM system should be. Some of these suggestions were agreed in the form of consensus statements, while others were proposed during in the course of other discussions.

The workshops agreed that the process should seek to "*satisfy the licence objectives to provide value for money based on whole life cost principles within the constraints of available budget*" (**W6**). Stakeholders agreed that the new system ought to align with Highways England's organisational objectives, but also be flexible to accommodate changes in organisational priorities in the future. The workshops agreed that the process should be transparent, robust and auditable and "*provide confidence in decisions*" (**W4**).

Implementation Several participants highlighted issues with rolling out new processes, including bugs in software tools and unanticipated conflicts with other tools and processes (**W7**). Accordingly, any new process should be rigorously trialled and rolled out slowly and with training where appropriate. Many participants stressed the importance of the value management workshops (**W5**) and technical reviews, stating a desire that the process should allow for a simple record to be produced of decisions made at these workshops (**W7**). A common theme was a desire to see a simplified, flexible process in which the invested effort in justifying a scheme is proportionate with the size of the scheme (**W4**).

5.5 Discussion and recommendations

5.5.1 Decision making workshops

In reviewing the questionnaire responses and engaging with stakeholders during the course of this review, it is clear that many of the stakeholders involved in the current Value Management process consider the Technical and Value Management Workshops to be the core of the current system. Across each of the sessions held, respondents repeatedly praised the importance of workshops, which provide an opportunity for all interested parties (service providers, representatives of commercial and technical teams in Highways England) to get into the same room and discuss a scheme. It was also noted that often the key decisions are made and agreed in the workshops, and that the formal process and paperwork can be a "*box ticking*" exercise afterwards. These sentiments are the basis of recommendation (**R1**).

Recommendation 1. *Future asset decision making process should include workshops to allow discussion of schemes between asset managers, technical specialists and commercial teams in an organisation.*

5.5.2 Auditable

One of the key benefits that stakeholders see in Highways England's current process is that it leaves a clear audit trail. Respondents were keen that a new process should maintain this important role in demonstrating that money has been spent well. This is the basis for recommendation (**R2**).

Recommendation 2. *Asset decision making processes should produce an auditable record of decision making. This should record risk factors and VfM, and satisfy the requirements of the relevant authorities (such as the National Audit Office).*

5.5.3 Scaleability

Many stakeholders, across all of the seven workshops, identified issues with the lack of scaleability of the current process. Anecdotal evidence was presented of schemes where the costs of Value Management process was a significant proportion of the overall scheme cost. Many participants expressed opinions that that the administrative burden of the process itself can prevent Value for Money from being achieved. Conversely, many participants were keen to stress the importance of a rigorous process to make decisions about spending large amounts of money. It is recommended that some degree of flexibility is built into the process, such that the administrative effort, detail of surveys and preliminary design work scale with the size of the scheme (**R3**).

Recommendation 3. *In designing asset decision making processes, it is recommended that the detail required to appraise schemes should be scaleable such that the effort is appropriate to the design stage, risk level and scheme size.*

5.5.4 Link to High Level Objectives and Service Provider Contract Forms

One of the core criticisms of the current Value Management process is that it has not kept up with changes in the higher level objectives of the organisation and that it now does not align well with Highways England's objectives as set out in the Road Investment Strategy. Many of the respondents expressed a desire to see any new process align better with Highways England's current higher level objective and maintain a link to the objectives and priorities as they change over time (**R4**). It was also noted that there are some instances where the processes do not align well with the existing service provider contracts, particularly the Asset Support Contract.

Recommendation 4. *There should be a clear link between decision making processes and an organisation's high level objectives. If possible this link should be flexible to reflect updated priorities.*

Recommendation 5. *The new process should aim to maintain compatibility with existing contracts, while also anticipating the needs of the future.*

5.5.5 The role of Value Management

Discussions were held over the course of this study regarding the position of Value Management within scheme identification and delivery. These discussions revealed inconsistency across the stakeholders in the perceived position of VM from needs identification to solutions development, and prioritisation. There would be benefit in a clearer focus of new processes to specific stages of scheme delivery (**R6**). Many stakeholders specifically highlighted a need for a new needs identification process, potentially adopting a risk-based approach (**R7**).

Recommendation 6. *In designing asset decision making processes, the role of the process should be clear and the process should target specified stages in the scheme development process.*

Recommendation 7. *Consideration should be given to development of distinct processes for identification of needs, appraisal of solution options and prioritisation of schemes.*

5.5.6 Flexibility & judgement

Several examples were presented of situations where 'common sense' would show a clear benefit in progressing a scheme, but where the current VM process does not produce a sufficiently high score. Many of these are situations where a scheme is addressing a new priority for Highways England, such as noise, which is not currently accounted for within the VM process. Other examples are for one-off situations where the benefits of the scheme do not fit within the framework of the current process. In situations such as this, it would seem sensible for a mechanism to exist to progress these schemes as exceptions. Given that such situations should be exceptions and will rely on the judgement of specialists, it would seem prudent to include safeguards, such as competency requirements for those signing off the decisions, to manage any increase in risk and maintain the same overall level of assurance as for decisions that fit within the standard process (**R8**).

Recommendation 8. *Asset decision making processes should allow a controlled mechanism whereby schemes which are absolutely necessary may be promoted on the judgement of experienced Engineers, potentially subject to a higher level of oversight. For example, this would allow important risk/safety schemes which do not offer high value for money to be progressed, and provide flexibility for the process to cope with unanticipated situations.*

5.6 Concluding remarks

This series of workshops and questionnaires with stakeholders in an asset decision making system has identified some highlighted the need to consider stakeholders in the design of asset decision making processes. The following points were of particular note:

- Stakeholders in the current Value Management system do not believe that the current process achieves Value for Money.
- The current processes were reported to take too much staff time, and require survey information that can be so expensive to obtain it prevents the schemes from being cost-effective.
- Participants reported that the formal process can often be a case of "*turning the handle*" on a "*box ticking exercise*" to put the paperwork in place for decisions that have already been made based on engineering judgement.
- Existing processes tend to put a focus on doing the minimum required maintenance, and manage assets in a reactive, rather than proactive, way. This focus comes at the expense of preventative maintenance schemes, which were reported to score too lowly in the existing process to be funded.
- Technical and commercial workshops were reported to be some of the most valuable aspects of the current processes.
- The participants highlighted a number of distinct stages that should be included in asset decision making processes: needs identification; appraisal of solution options; prioritisation of schemes; and value-engineering during detailed design.

Many of the themes of this chapter are picked up in the analysis in subsequent chapters. Chapter 9 sets out an argument that, rather than processes appraising and prioritising whether to fund schemes that have been put forward, it would be more sensible to review asset needs and ask "*when is the best time to intervene*". In common with processes at other UK asset owners (e.g LoBEG 2018, chapter 4), the decisions in the current Highways England Value Management process make decisions at an individual asset level, begging the question of what the system-level response is when this process is applied to a stock of thousands of assets. Chapter 9 analyses the stock-level response in terms of trends in condition and spending that can result from asset-level decision making and shows that organisations should seek to manage their backlog and maintain their stock in a steady state of good repair to maintain control of spending and avoid an 'asset management timebomb' (Thurlby, 2013). This chapter provides a counter-point to the data-driven analytical methods in Chapter 7 - while there is exciting potential for data science techniques to transform asset management, any change must also consider the role of individuals and organisations within the system.

Chapter 6

Reliability of Visual Inspection Data

Aspects of this chapter are based on work presented in Bennetts et al. *(2017) and have been reported in Bennetts* et al. *(2018a).*

Bennetts J., Webb G. T. & Denton S. R. (2017) *The State of Bridge Infrastructure. Technical report,* WSP UK ltd on behalf of Highways England

Bennetts J., Webb G. T., Vardanega P. J., Denton S. R. & Loudon N. (2018a) Quantifying Uncertainty in Visual Inspection Data. In: *Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges: Proceedings of the Ninth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2018), 9-13 July 2018, Melbourne, Australia.* (Powers N., Frangopol D. M., Al-Mahaidi R. & Capriani C., eds), Taylor and Francis, London, UK, pp. 2252–2259

6.1 Introduction

Visual inspection is the most commonly used method of condition monitoring for bridges in the UK (e.g. McRobbie *et al.* 2015; Bennetts *et al.* 2016, chapter 4) and can be considered to be a form of 'Damage Detection' Structural Health Monitoring according to Webb *et al.* (2015). Studies have raised concerns regarding the reliability of visual inspection data due to human factors (See *et al.*, 2017), with several highlighting variability in the results of visual inspection of bridges due to inconsistencies in the recording of defects between individual inspectors (Moore *et al.* 2001b; Graybeal *et al.* 2002; Lea & Middleton 2002; Middleton 2004).

This chapter reports the results of a study which compared scoring of bridge defects by pairs of independent inspectors across 200 bridge structures on England's strategic road network. A sample of 200 structures was selected to be representative of Highways England's stock with regard to, inter alia, *age, condition* and *structural form.* Routine Principal Inspections for these sample structures, undertaken every six years by the relevant maintaining agents, were also attended by inspectors from WSP Ltd, with defects scored independently by each inspector.

The results of these comparisons were used to derive an empirical profile of the uncertainty in different individual defect severity and extent scores. Statistical methods were then used to derive empirical probability density functions for the values of bridge and stock level condition metrics according to the widely adopted *Bridge Condition Indicator* system. The reported results highlight trends in the reliability of individual defect scores and the impact of uncertainty on commonly used performance metrics.

6.2 Methodology

6.2.1 Random sample

A stratified sample of 200 bridges was selected by the author from Highways England's stock for inclusion in this research. This sample was selected to be representative of the whole bridge stock, taking into account the following attributes: *Condition; Deck Type; Construction Type; Road Class; Age Group; Structure Type; Maintenance Region*; and *Type of Tensioning*. For example, the proportion of bridges in the sample with post-tensioning was selected to be the same as the proportion of post-tensioned structures in Highways England's whole stock of bridges.

The sample was selected computationally by randomly choosing several thousand possible samples of 200 from the list of structures due to be inspected over the duration of the project, and then selecting the random sample which was the best fit for the whole stock. The quality of fit, Q_{sample}, was evaluated as the sum of the mean of the squares of the differences in the proportions of each attribute value in each attribute, with the lower numbers indicating a better fit as shown in Equation 6.1.

$$Q_{sample} = \sum_{attributes} \frac{\sum_{attribute\ values}[P_{stock} - P_{sample}]^2}{N_{attribute\ values}} \tag{6.1}$$

6.2.2 Independent scoring of defects

For each of the 200 bridges in the sample, a WSP bridge inspector attended the site to independently inspect and record a sample of the defects present on the structure. For the large majority of the bridges in the sample, this coincided with the Service Providers' Principal Inspection. However, for a small number of the sample bridges, the independent inspectors visited the structure during a separate shift. For each visit, the inspectors recorded independent defect type, severity and extent information for a subset of the defects on the structure. These were limited to those visible at close quarters on the structure using the available access. 1373 individual defects were independently recorded by WSP's inspectors, of which 988 (72%) could be directly compared to those entered by the Service Providers' inspectors. Of the 28% of defects recorded by WSP's inspectors that could not be directly-compared, many were due to differences in whether defects were given a single defect entry or multiple entries. For example, a paintwork defect where the steel substrate is rusting may have been logged as a corrosion defect by one engineer, and a paintwork and a corrosion defect by the other. Because the WSP inspectors only graded a sample of defects on each bridge, the number of defects that could not be directly compared between inspectors does not necessarily equal the number of defects that were 'missed' at each inspection. The data-set also does not show the number of defects that WSP's inspectors missed. Notwithstanding, the figure of 28% is high and suggests that there may be differences in the defects identified and recorded by different inspectors. It is therefore likely that there are many bridge defects which have not been recorded on the asset database.

6.2.3 Qualitative site report

At each of the 200 sample structures, the attendant WSP Inspector was asked to complete a 'Benchmark Inspection Report', containing qualitative responses to questions on the following topics:

Inspection details e.g. weather, time of day, duration, dates, equipment used, traffic management

Testing details

Reliability of inspection data e.g. suitability of resources, quality of inspection, any impediments to inspection, efficiency

Bridge design and construction e.g. performance of the structure, quality of construction, water management

Bridge maintenance and repairs e.g. status of maintenance actions, performance of repairs

These reports were completed by hand on-site and typed up to produce a digital record. A sample of a completed report is included in Appendix D.1.

These documents, containing written descriptions and comments from WSP's inspectors have been processed using Computer Aided Qualitative Data Analysis (CAQDAS) techniques, whereby the text records were coded into themes against the project's research questions. Coding involved highlighting excerpts of text with digital highlighter pens linked to the relevant Key Questions. This allowed the various data sources to be brought together as a narrative on each of the key research questions. Further detail on CAQDAS techniques is presented in Section 3.2. For research question themes that required a subjective judgement, evidence was scored on a scale from 0 to 5. The scale used for each of these questions is presented in Appendix D.2.

The results of the processing of these reports is presented in Section 3.2, and also in Chapter 7.

6.2.4 Testing

6.2.4.1 Testing specification

Testing was specified on components of the sample structures based on a standard schedule. Individual adjustments were made to this schedule based on a review of previous inspection reports obtained from SMIS and the record drawings, taking into account constraints on access and the overall age and condition of the structure. Where it was considered that the testing would be unlikely to produce new or additional condition information due to recent pre-existing testing on a structure, resources were applied elsewhere. The testing was scoped and initially scheduled to align with the Principal Inspection process, based on the understanding that where possible, the Service Providers would deploy inspection and testing resources concurrently to maximise the use of access and traffic management and thus reduce impact on the highway network overall.

Testing was specified on common components and systems that are known to be affected by hidden defects that are not necessarily detectable by visual means alone. This testing comprised a suite of testing or Special Inspections on reinforced concrete elements, protective paint systems and ultrasonic thickness testing on hollow steel components. The specified testing operations are detailed below.

Testing of concrete components Concrete condition assessment on typical 2m x 1m test areas, or 3 grid points on a parapet string course, in locations subject to potential or actual joint leakage and/or traffic spray, or displaying signs of existing deterioration/cracking. Testing comprised:

- Visual inspection
- Covermeter survey
- Half- cell potential survey
- Concrete resistivity (2 probe test)
- Insitu carbonation test
- Incremental percussive sample drilling for subsequent chloride ion determination (1 location per test area unless otherwise agreed)
- Drillings for chloride and carbonation samples typically 4 x 25mm depths, minimum sampling depth to be 25mm beyond mean rebar cover
- Delamination testing (hammer tap test)

Testing of steel components Steel condition testing typically at locations of deck joints and mid-span of primary and secondary members. Testing comprised:

- Visual examination
- Measurement of loss of section in locations of apparent corrosion
- Non-destructive ultrasonic measurement of structural component thickness
- Connection check

- Coating check - full examination and testing of paint sample at 3 representative locations to the structure unless the paint is of different types / thickness / condition etc., which requires that more widespread detailed paint examination is required
- Coating examination using x15 illuminated magnifier
- Paint adhesion testing by cross cuts
- Visual examination and ultrasonic weld testing in representative locations
- Carry out in-situ paint testing to check for lead or other harmful substances

6.2.4.2 Processing and interpretation of testing results

Testing results were received from over 300 investigations on 138 of the structures from the benchmark sample of 200. These reports were reviewed by WSP engineers experienced in structure degradation testing and interpretation of results. Comparisons of the defects noted in the reports produced by the Service Providers' supply chain testing companies were made against related defects recorded in the Principal Inspection reports and the Benchmark Inspection Records.

The relevant defects were scored as to whether the testing suggested that the condition of the component, as recorded in SMIS or at the Benchmark Inspection, was correct with regard to the type, severity and extent of any relevant defects. Furthermore, if the testing suggested a change to the severity or extent of any defects should be applied, the degree of change was graded on a five point scale for both severity and extent as follows:

1. Severity / Extent much greater than visual
2. Severity / Extent greater than visual
3. No change in Severity / Extent
4. Severity / Extent less than visual
5. Severity / Extent much less than visual

Commentary was provided against each testing report regarding quality and any anomalies. These comparisons were recorded on a standard excel form which were compiled and analysed using the Python 3.x programming language.

6.3 Data analysis - Visual inspection comparisons

6.3.1 Reliability of defect recording

For 385 (28%) of the defects recorded by WSP's inspectors, it was not possible to identify an equivalent defect in the Service Providers' Principal Inspection reports. This indicates variability in the reliability of defect identification by inspectors during visual inspections. Across the 988 independently recorded defects that could be directly compared to those recorded by the Service Providers as part of their Principal Inspection, 21% agreed on the assigned defect type, defect severity and extent. Overall, for 58% of the compared defects there was agreement on the type (e.g. *Map cracking*) of defect assigned, and agreement on the overall class of defect (e.g. *Cracks in concrete or masonry*) for 78%.

The level of agreement of defect types varied between different classes of defects, as shown in Figure 6.1. Particularly low reliability of defect class assignment was found within the *Cracks in concrete or masonry* and *Loss of concrete or masonry* defect classes. Investigation into the causes of these inconsistencies suggests that the process allows too many options of defect type within these classes. Consequently accuracy has been compromised in exchange for the availability of greater precision in defect type assignment. Furthermore, it was noted that while some defect types can only be confirmed through laboratory testing, the codes for these defects could, and had been, applied based only on visual inspection.

Similar results were found for the probabilities of the two inspectors recording the same defect severity or extent, with agreement of defect severity assignment for 53% of the compared defects, and agreement on defect extent for 59%. The same defect severity and extent were applied by the two inspectors for 34% of defects compared.

6.3.2 Element Condition Scores

For each recorded defect the extent and severity scores have been added to calculate an element condition score (ECS), giving a single measure to allow a comparison to be made between the two different inspectors (i.e. one each from WSP Ltd and Highways England's Service Provider for the maintenance area). These comparisons are presented in Figure 6.2, with each of the 988 comparisons represented as a blue marker. Due to the discrete nature of defect scores there are many overlapping markers. Red shading has therefore been added to indicate the density of markers at any point on the plot. Also shown, at the top and right of the plot, are histograms and gaussian kernel density estimations to provide an indication of the distribution of the scores from each inspector. While the two inspectors assigned the same, or a similar, defect severity and extent for many of the observed defects, there were substantial numbers of defects with a difference in ECS of more than 1. There were considerable discrepancies between the two inspectors' assessments of the severity of some defects, suggesting that the condition data for some structures could be markedly different, depending which individual inspector conducted the inspection.

6.3.3 Trends in the reliability of defect scoring

6.3.3.1 Importance dendrograms

Importance dendrograms allow presentation of the categorical factors that most influence a target variable - using decision tree machine learning algorithms (Quinlan, 1986) as a data mining tool.

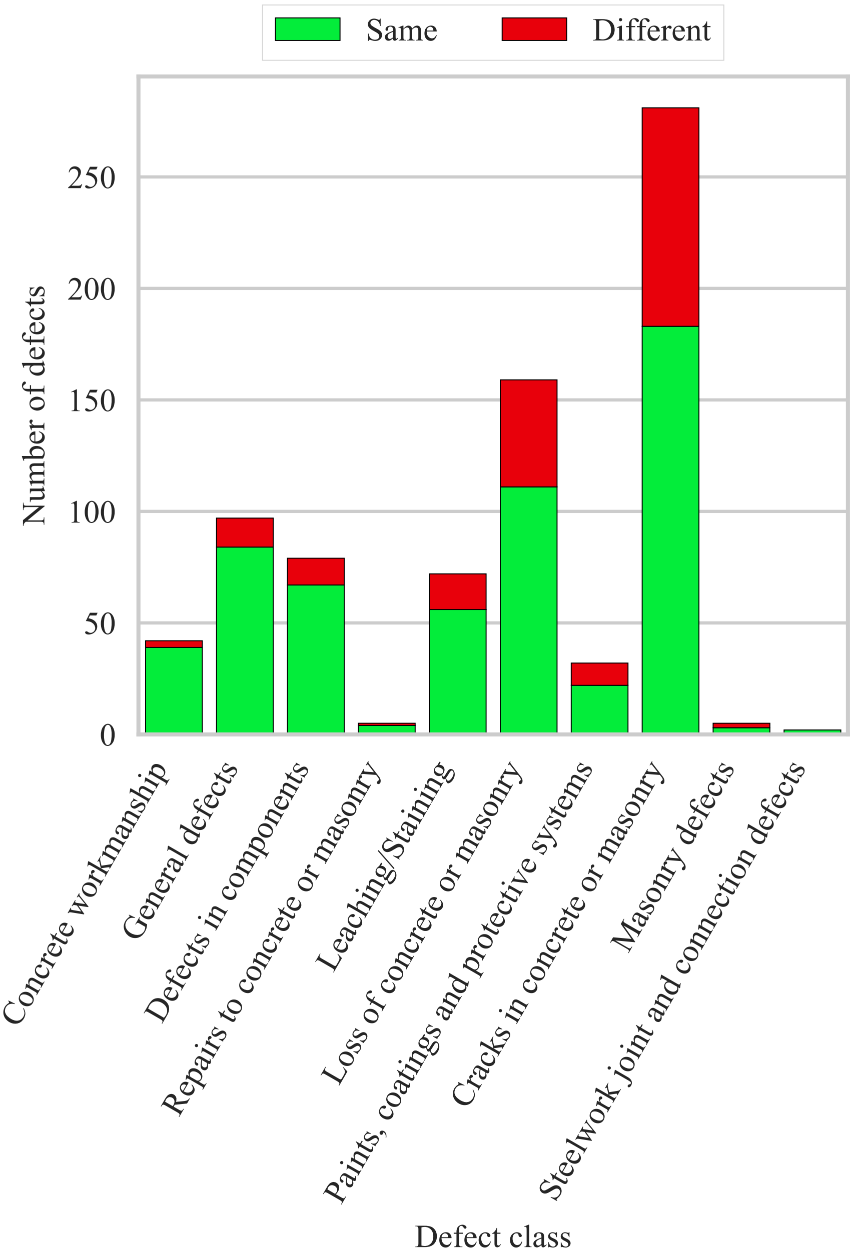

Figure 6.1: Comparison of defect type allocated by Service Provider inspector and WSP inspector for the defects included in this study, grouped by defect class.

Importance dendrograms are discussed in more detail in Section 3.4. To explore the factors affecting the reliability of defect scoring, an importance dendrogram tree was generated to find the most informative multi-factor trends in the variation of defect score assignment (ECS) between two inspectors. For each compared defect the absolute difference between the ECS recorded by the WSP inspector and the Service Provider was calculated and banded into five groups as evenly as possible

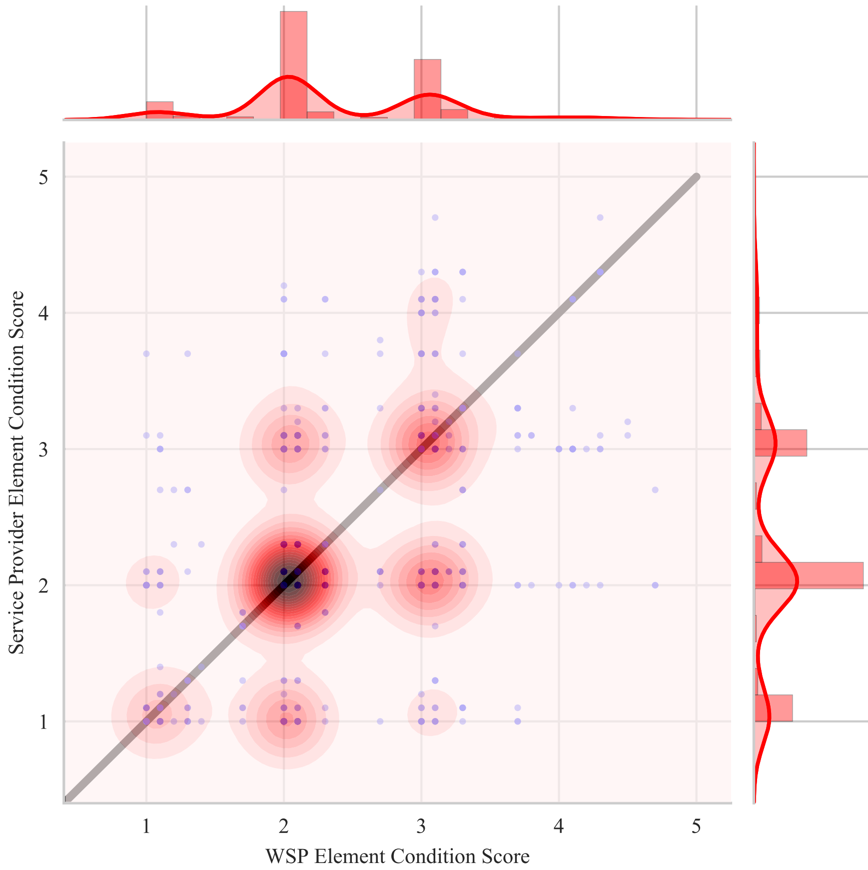

Figure 6.2: Comparison of element condition score allocated by Service Provider inspector and WSP inspector for the 988 defects included in the study. Red shading has been added to indicate the density of markers at any point on the plot.

from those which were the same, to those which were the most different. Each pie chart in the dendrogram has been drawn to represent the distribution of the ECS difference bandings within the sub-population below that point in the tree structure (Figure 6.3). The top *'All comparisons'* pie-chart represents the distribution of ECS difference in the full set of defect comparisons.

At each splitting point, the optimum attribute has been selected to partition the data in the way which provides the most information. The reduction in Shannon entropy (Shannon, 1948) has been used to measure the information gained by a partition. For this measure, a perfect partition would be an attribute that perfectly split the structures into each of the ECS difference bands, whereas the worst possible partition would result in sub-populations that each had an even distribution of ECS difference within them. The size of each node's pie-chart has been drawn inversely proportional to its entropy and larger pie-charts have been plotted further from their parent node. This allows the most informative partitions to be readily identified. The following attributes were given to the algorithm from which it selected the optimum tree topology: *Component, WSP Class, WSP Extent, WSP Severity,* *Structure type, Construction type, Deck type, Structure use, Structure condition band, Distance from coast, Region, Age group*, where:

WSP Class, WSP Extent & WSP Severity are the defect class, extent and severity, as recorded by the WSP inspector on site.

Age group splits the bridges into five bands from youngest to oldest with the same number of bridges in each band.

Structure condition band splits the bridges into five bands by their BCI_{Ave} condition score, from best to worst.

Nodes, and corresponding branches, have only been drawn if they represent at least 10 comparisons. The depth of the tree was limited to 3 partitions.

6.3.3.2 Trends

Figure 6.3 shows the most informative variables which affected the variation in ECS between two inspectors. The *defect extent* had a significant influence. There was a much greater variation in ECS for defects with greater extent, than for those with lesser extents. This suggests that it is much harder to judge the severity of extensive defects. *Component type* was an important factor. Components such as *Road Vehicle Restraint Systems* and *Supports* were seen to exhibit much greater variation in scoring than components such as *Crossheads, Expansion joints* and *Wingwalls*. There was also a large degree of variation between different maintenance regions, suggesting that inspection guidance and practice are not consistent across the country. Structure details such as *age, structural form, construction material, road class*, and overall *structure condition* have a lesser influence on the reliability of defect scoring.

6.4 Data analysis - Comparison of testing data with visual inspection

Structural investigations were carried out on a total of 138 structures. The results of each of these investigations have been reviewed and compared to the defect extent and severity data recorded during visual inspections, to determine whether incorporation of the testing results would result in any changes to the defect's scoring. The results from these comparisons are presented in Figures 6.4 to 6.6.

The results of each structural investigation have been reviewed and compared with the defects recorded during visual inspections of the structures. Figure 6.4 illustrates changes in recorded severity and extent scores following evaluation of the testing results. It can be seen that testing results were more likely to lead to an increase in the severity of a defect than to lead to a decrease. This is also reflected in Figures 6.5 and 6.6 where it can be seen that the greatest proportion of defects which were altered by the testing results were those which were considered by the inspector to be of fairly

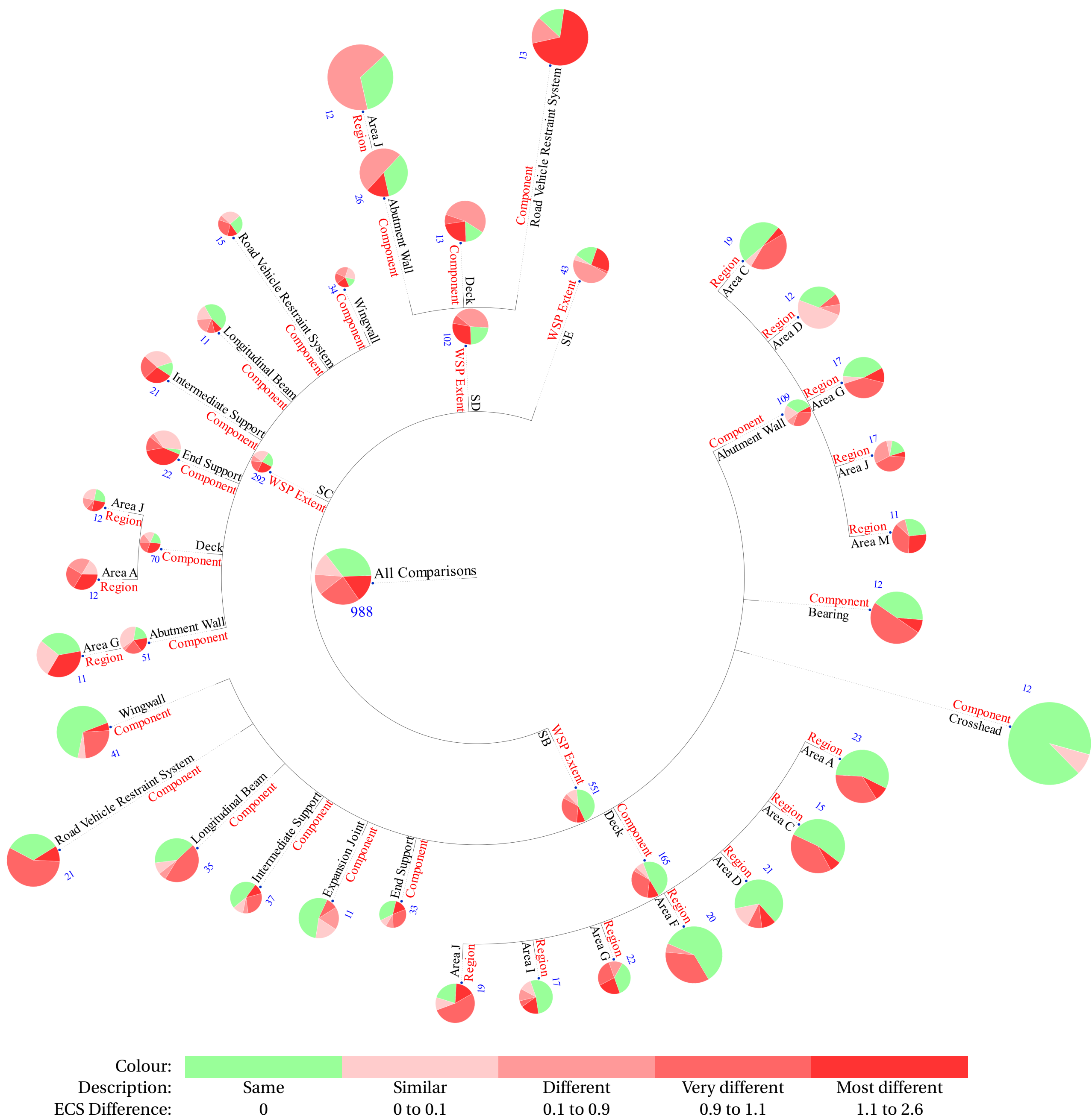

Figure 6.3: Importance dendrogram - Visual inspection reliability.
Importance Dendrogram, showing the factors that most affect defect scoring agreement between inspectors. The blue number next to each pie chart denotes the number of comparisons that are included in that sub-population. The red text on each branch of the tree represents the attribute that the dataset has been partitioned by at that level, and the black text represents the value of the attribute.

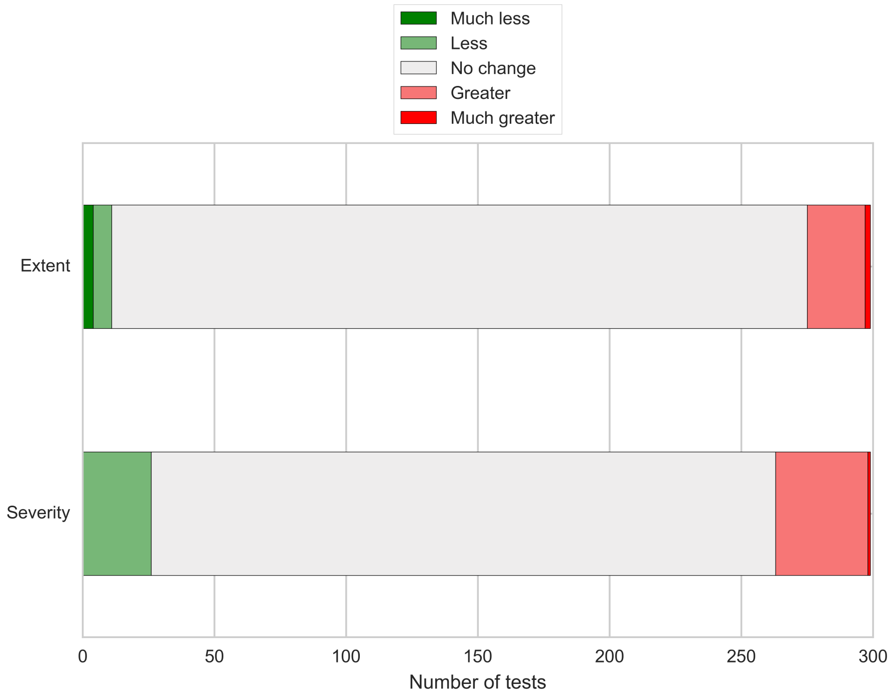

Figure 6.4: Changes in recorded severity and extent scores following results from testing.
This plot shows the changes to recorded severity and extent scores following interpretation of the structural investigation results.

low extent or severity. However, in the vast majority of cases (94%), evaluation of the testing results did not result in any changes to the defect scores allocated by inspectors following visual inspections. One of the primary motivations for including the testing work was for the results of the testing on the sample structures to be used to calibrate the overall condition of all assets on the network. However, with the results having shown limited updating of condition based on testing, this calibration exercise was not considered worthwhile.

The results showed that 94% of the recorded defect types were not altered following interpretation of the structural investigation results. However, where the defect type was altered this was usually for one of the following reasons:

- Incorrect identification of concrete cracking, spalling, leaching or staining.
- Differences in classification of water related defects, such as whether there was running water, or water stains. These differences may have been a result of the testing often being undertaken at a different time (and hence in different weather conditions) to the visual inspections.
- The testing identified that the defect had been assigned to the wrong component on the structure.

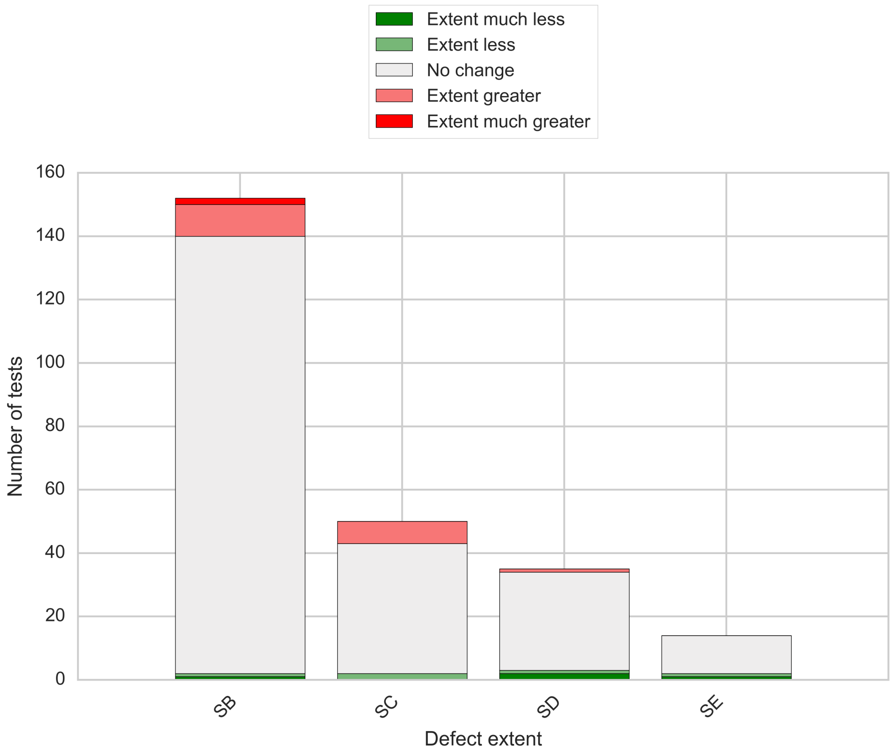

Figure 6.5: Changes in recorded extent scores following results from testing, grouped by defect extent. This plot shows, for each defect extent (prior to testing), the changes to recorded extent scores which resulted from interpretation of the structural investigation results.

As discussed in Section 6.3.1, there are currently a large number of different types of concrete defect available in SMIS, many of which could be difficult or impossible to differentiate visually. Testing data could be used to identify likely defect causes with much greater reliability than visual inspections. Although this information is not included in the BCI score calculations, an understanding of the type of defect is vital for predicting likely future behaviour and hence maintenance requirements. Quantifiable information from testing may also lead to an improved understanding of any changes over time, which may not be apparent visually. This information could also be used to help predict future deterioration rates and likely maintenance needs.

Carrying out intrusive structural testing is expensive, especially if only a small proportion of tests produce information which improves the understanding of defects. However, the value of the additional information is extremely difficult to quantify, partly due to the lack of information available about maintenance and repair costs. The results presented here suggest that testing should not be aimed at validating BCI scores, however there are other areas where testing data has the potential to be beneficial. In addition to providing extra information to help remedial works to be planned efficiently or undertaken proactively before the problem deteriorates further, quantitative testing data could also be incorporated into the development of future deterioration models.

It is noted that when testing was undertaken on structures it was typically carried out during

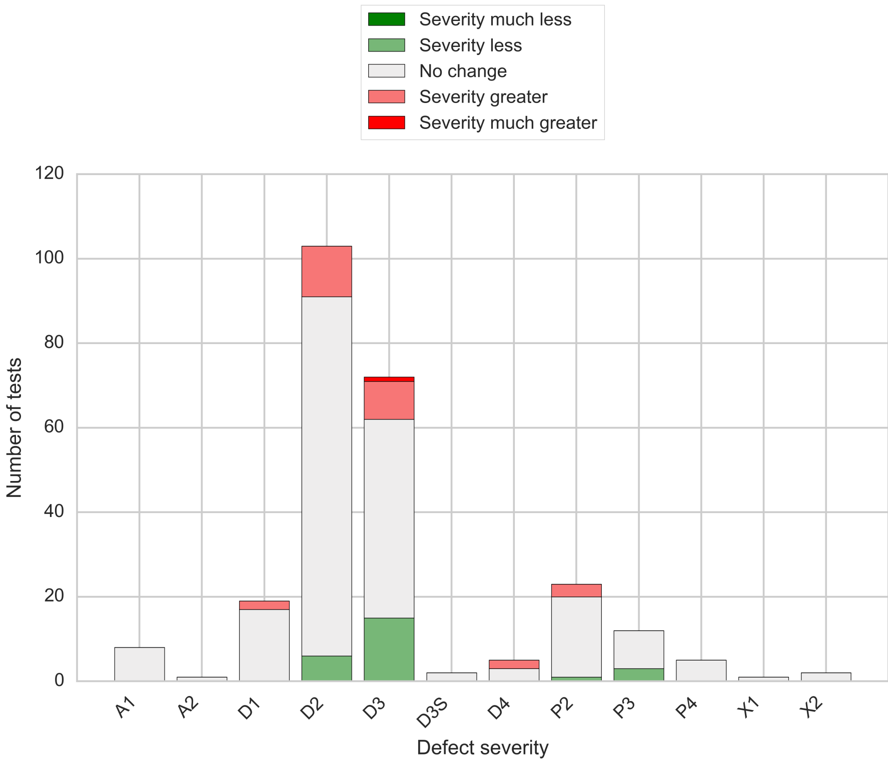

Figure 6.6: Changes in recorded severity scores following results from testing, grouped by defect severity.
This plot shows, for each defect severity (prior to testing), the changes to recorded extent scores which resulted from interpretation of the structural investigation results.

a Special Inspection and not at the same time as a Principal Inspection. This clearly introduced inefficiencies due to extra access and mobilisation costs, and suggests that it would not generally be feasible currently to include such testing routinely alongside visual inspections.

6.5 Data analysis - Analysis of Benchmark Inspection Reports

6.5.1 BD 63 compliance

WSP's inspectors were asked to comment upon whether the inspections witnessed were in full compliance with BD 63/07 and whether they were in the spirit of BD 63/07. These responses were qualitatively reviewed and scored on a scale from 0 to 5, where 5 represents full compliance. Figures 6.8 and 6.7 present the results, grouped by maintenance area. 81% of the inspections witnessed were found to be fully compliant with BD 63/07, and 93% were deemed to be fully in the spirit of BD 63/07.

Of structures that were deemed to be fully in the spirit of BD 63/07, but not fully compliant, the most common reason was that areas of the structure could not be reasonably accessed to within touching distance. For example, for structures with a support adjacent to the edge of the carriageway,

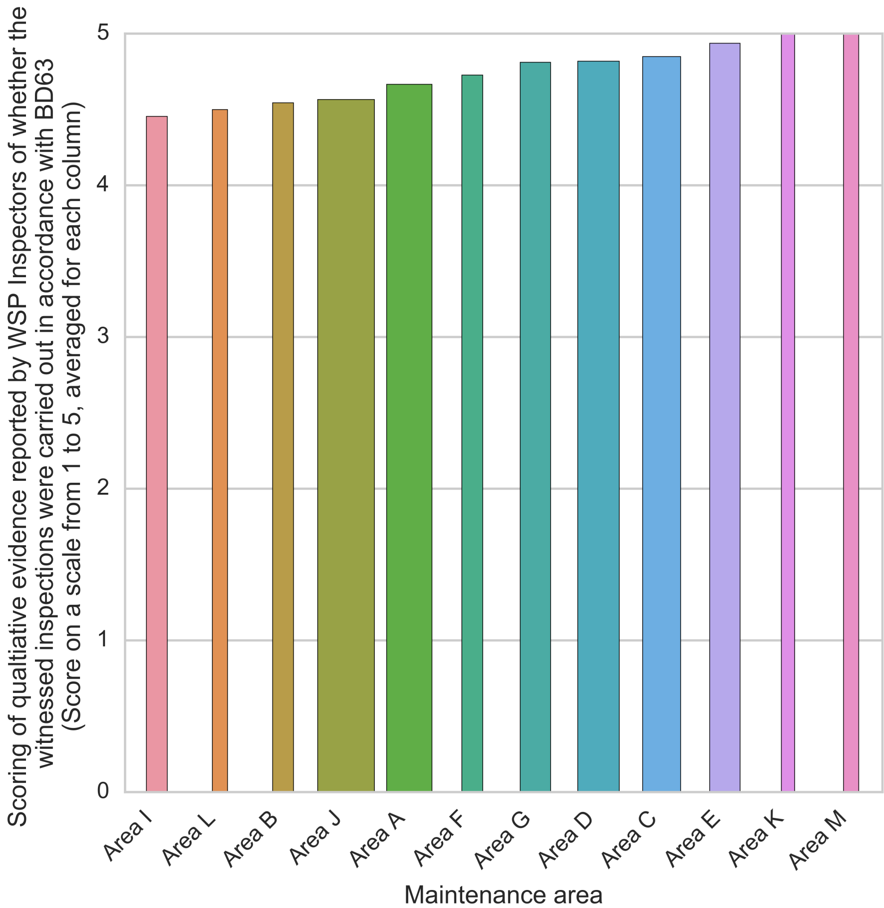

Figure 6.7: Strict compliance with BD63 by maintenance area.
This plot of qualitative weightings applied to codes in Dedoose.com, shows the average scores applied on a scale from 0-5 for strict compliance with BD63, split into categories of maintenance area. Only one weighted code per structure in the sample of 200 has been included, with the most critical taken if there was more than one weighted code for *strict compliance with BD63* applied to a Benchmark Inspection report. The weighted codes were applied subjectively to extracts of text from the Benchmark Inspection reports, where the WSP inspector that witnessed the Benchmark Inspection recorded comments and observations that provide evidence to give judgement on strict compliance with BD63. The widths of the bars have been scaled to indicate the number of codes (taking only one per Benchmark Inspection report) applied to each category of maintenance area. The categories are displayed in order of average applied weight.

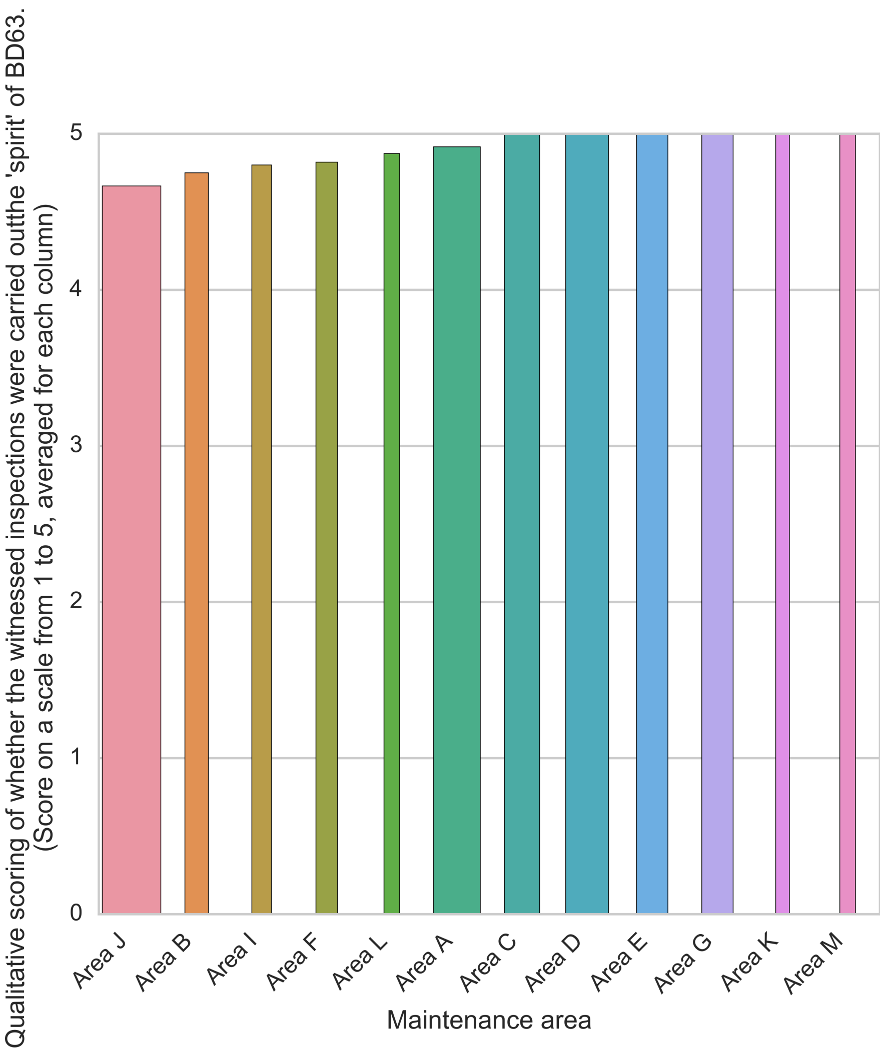

Figure 6.8: Compliance with spirit of BD63 by maintenance area.
This plot of qualitative weightings applied to codes in Dedoose.com, shows the average scores applied on a scale from 0-5 for compliance with spirit of BD63, split into categories of maintenance area. Only one weighted code per structure in the sample of 200 has been included, with the most critical taken if there was more than one weighted code for compliance with spirit of BD63 applied to a Benchmark Inspection report. The weighted codes were applied subjectively to extracts of text from the Benchmark Inspection reports, where the WSP inspector that witnessed the Benchmark Inspection recorded comments and observations that provide evidence to give judgement on compliance with spirit of BD63. The widths of the bars have been scaled to indicate the number of codes (taking only one per Benchmark Inspection report) applied to each category of maintenance area. The categories are displayed in order of average applied weight.

it could be impossible to access the deck soffit of the side spans with a MEWP mounted on the carriageway. Similarly, the geometry of underbridge units can mean that it is not possible to achieve a full touching distance inspection of some sections of a structure. Failure to measure headrooms was another common reason for inspections to be deemed non-compliant with BD 63/07. There were a very small number of inspections where insufficient time or access equipment were dedicated to the inspection. A number of inspections in one maintenance area, Area 9, were noted to have been completed too quickly for a thorough inspection.

6.5.2 Elements not inspected

During the Benchmark Inspections WSP's inspectors were also asked to note any structural elements for which data was not collected. At the majority of inspections it was reported that all elements were inspected, however there were some cases where this was not the case, primarily for the reasons listed below:

- The most commonly recorded reason for not inspecting all components was a lack of suitable access. In some cases the design of the structure did not leave sufficient space for inspectors to access areas such as bearing shelves, half joints, and the top surfaces of beams. In other cases access to locations such as the mid-span of beams was difficult or impractical with the access equipment available (in one location access for an underbridge unit was blocked by the position of a lighting column).
- Components such as waterproofing and foundations could not be inspected as they were buried. Cladding was also highlighted as a problem where it inhibited the ability to inspect the underlying structural members.
- There were a small number of instances where the reasons for not inspecting all structural elements appeared to be due to insufficient planning. In some inspections access to wingwalls was restricted due to the amount of vegetation present. During other inspections there were parts of the structure which could not be accessed due to the scope of Traffic Management provided. Finally, there were two instances where steel thickness could not be measured as no suitable measuring equipment was brought to site.

6.5.3 Suitability of inspectors

During the Benchmark Inspections WSP's inspectors were asked to comment on the suitability of the Service Providers' inspectors. With the exception of a few isolated issues it was reported that the majority of inspectors appeared experienced and competent to undertake the inspection being observed. WSP's inspectors' comments have also been subjectively scored on a scale from 0 to 5, with 0 indicating a low degree of suitability and 5 indicating a high degree of suitability. Most scores were very high, reinforcing the view that the suitability of inspectors appeared to be good in the majority of cases. Very little difference in the degree of suitability was recorded for structures of different conditions and construction types. This again suggests that the majority of inspectors were suitably experienced and competent to undertake the inspections they had been assigned to. Some variation was observed between the apparent suitability of inspectors in different maintenance areas. However, there does not appear to be any correlation between these results and the variation in reliability of inspection data across different maintenance areas (as discussed in section 6.3.1). It therefore appears that the competency of bridge inspectors is not a significant factor influencing the apparent variation of inspection reliability observed between different maintenance areas of Highways England's network. It is noted that there are currently a lack of consistent guidance documents which are up to date with the system for defect reporting which is currently used in SMIS. This lack of universal guidance may have contributed to inconsistencies between different maintenance areas.

6.5.4 Is inspection quality affected by the time of day or the weather?

There were significant differences in the number of benchmark inspections which were undertaken during day and night in each maintenance area. However, there does not appear to be any correlation with the observed variability of defect scoring in each maintenance area. Additionally, the time of inspection appeared to have very little influence on the perceived compliance with BD 63/07. These findings suggest that the quality of inspections undertaken at different times was relatively consistent.

However, significantly stronger evidence of poor quality of construction was observed during daytime inspections than during those undertaken at night. Furthermore, there were a significant number of inspections, primarily undertaken at night, where insufficient lighting was highlighted as a hindrance to the inspection. This demonstrates the importance of providing sufficient lighting during inspections to ensure that defects are not overlooked and it is recommended that provisions are made to ensure that adequate lighting is always available for inspections.

Significantly stronger evidence of poor performance of water management was recorded during inspections undertaken in inclement weather. This is likely to be due to the fact that ineffective water management will be much easier to identify whilst it is raining. Inspectors should therefore take particular care when inspecting structures during fine weather conditions to ensure that defects relating to water management are not overlooked.

6.5.5 Noted areas for improvement of inspections

During the benchmark inspections WSP's inspectors were asked to comment on the reliability of inspection results and highlight potential areas for improvement. In many of the inspections, access difficulties were encountered and it was suggested that vegetation clearance or routine maintenance undertaken prior to the inspection would have been beneficial. Additionally, there were a number of inspections where difficulties were encountered with the access equipment which was used. For example there were situations when the MEWP employed was found to be too small to reach all areas of the structure, and others where the size of the MEWP made it impossible to get close enough to the structure. It would be beneficial for information relating to access arrangements and requirements to be stored within SMIS so that such problems are not encountered repeatedly.

6.6 Implications of defect rating variability on condition metrics

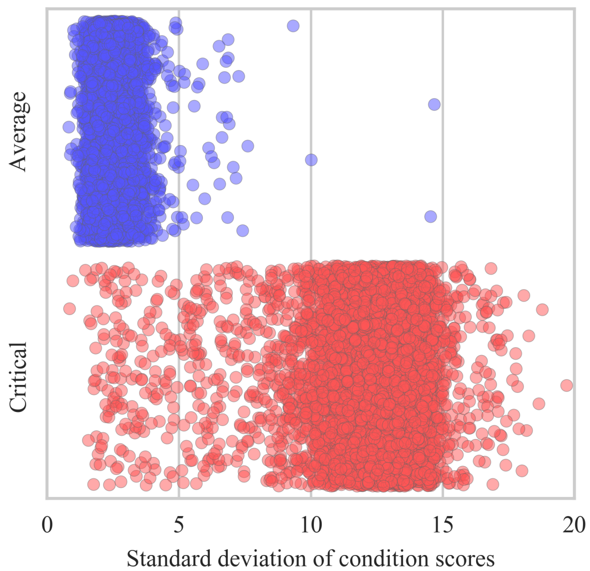

Figure 6.9: Standard deviation of condition scores obtained for each individual structure during Monte Carlo analysis

Given the variability of the visual inspection data collected by the owners of highway bridges, it is important to understand how this uncertainty affects derived metrics, which are used to inform strategy and decision making. The *Bridge Condition Indicator* calculation process is convoluted, and includes some non-linear steps, which means that it is difficult to derive directly the uncertainty in the resulting metrics from the uncertainty in the underlying data. Instead, Monte Carlo simulations have been used to derive this uncertainty empirically.

6.6.1 Monte Carlo simulations

The 988 individual defect comparisons have been used to generate a table of probabilities mapping, for each extent code allocated by one inspector, the probabilities that a second inspector would allocate each of the possible extent codes. To avoid an implicit assumption that one inspector was 'correct', each observation was counted twice: once with the WSP inspector as Inspector 1 and once with the Service Provider's inspector as Inspector 1. This exercise was repeated for the severity scores. The resulting probabilities are presented in Table 6.1 and Table 6.2.

The probabilities have been derived from data from the sample of 200 structures only, however, since the structures were selected as a representative sample of the entire stock, it has been assumed that they are applicable to data from all structures in the stock. It is noted that no defects with a severity score of 4.1 or 5 were observed, by either inspector, on any of the structures in the sample. In the absence of additional information it has been assumed, for this analysis, that there was no variability in the scoring of defects with these severities. This will not significantly affect the results since defects with a severity score of 4.1 or 5 represented fewer than 1% of the approximately 500,000 currently valid defects in the SMIS database.

The probability tables were used to vary the severity and extent scores for each of the currently valid defects in the SMIS database. These altered scores were then used to calculate new BCI_{Ave} and BCI_{Crit} scores for each bridge. This analysis was repeated for 1000 simulations.

Table 6.1: Probability table for defect extent codes

		Extent Code Allocated By Inspector 1			
		SB	SC	SD	SE
Probability of	SB	0.735	0.436	0.266	0.312
Inspector 2	SC	0.196	0.419	0.293	0.219
Allocating	SD	0.043	0.105	0.351	0.177
Extent Code	SE	0.026	0.040	0.090	0.292

Table 6.2: Probability table for defect severity codes

		Severity score allocated by Inspector 1								
		1	1.1	2	3	3.1	4	4.1	4.2	5
Probability of Inspector 2 allocating Severity score	1	0.46	0.23	0.10	0.05	0.04	0.00	0.00	0.00	0.00
	1.1	0.03	0.31	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	2	0.39	0.31	0.66	0.36	0.33	0.16	0.00	0.33	0.00
	3	0.11	0.15	0.20	0.50	0.25	0.53	0.00	0.33	0.00
	3.1	0.00	0.00	0.01	0.01	0.25	0.01	0.00	0.33	0.00
	4	0.00	0.00	0.01	0.06	0.04	0.29	0.00	0.00	0.00
	4.1	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
	4.2	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00
	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

6.6.2 Uncertainty in BCI scores for individual structures

This analysis gives a set of plausible alternative values for the BCI scores for each individual structure. The level of uncertainty in BCI scores calculated by this method is dependent on a structure's

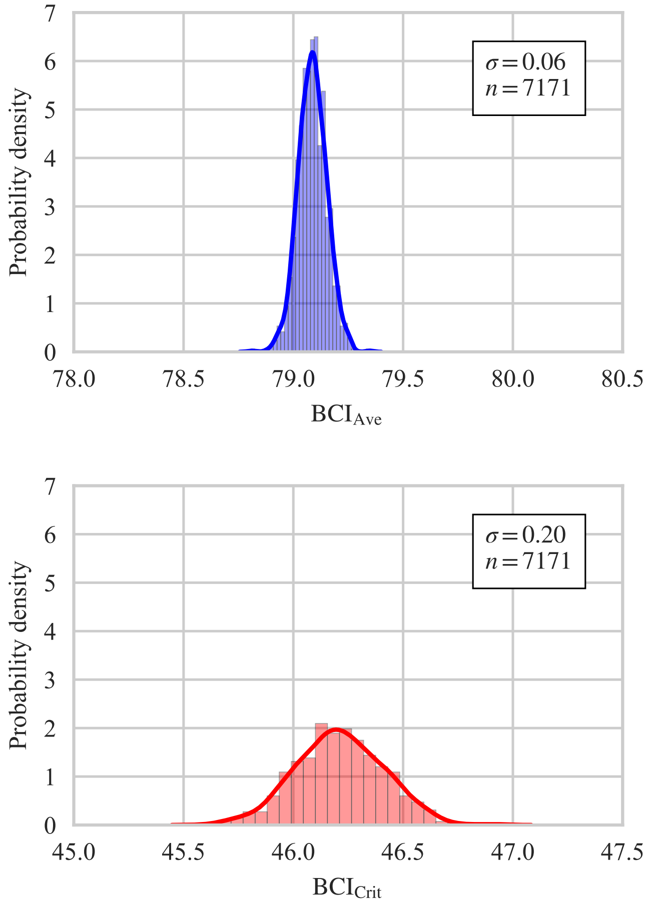

Figure 6.10: Empirical probability density function for the value of the BCI_{Ave} (top) and BCI_{Crit} (bottom) score for all structures in the stock.
The solid lines show a Gaussian fit over the results, with the corresponding standard deviation (σ), and the number of bridges (n) in the sample given in the box).

inventory and defect assignments. It is therefore not possible to derive a definitive probability density function around a mean that would be valid for all structures. Instead, the standard deviations of each of these sets of alternative values have been plotted in Figure 6.9 for each of the approximately 7100 bridges on Highways England's network for which data was available. This shows that there is considerable uncertainty in the condition indicator scores for individual bridges; the BCI_{Ave} scores for most bridges have standard deviations of between 2 and 4 points, and the BCI_{Crit} scores for most bridges have standard deviations of between 10 and 15 points. The larger degree of uncertainty for BCI_{Crit} scores is due to them being governed by a very small number of defects on key structural components. In contrast, the BCI_{Ave} scores include defects from multiple component types and are therefore much less sensitive to variations in the scoring of individual defects.

In considering the implication of these results, it is useful to consider approximately what magnitude of change in a structure's condition score between consecutive inspections would be considered statistically significant. For a 95% confidence level, it is typically assumed that a change of two standard deviations would be required for the result to be considered significant. It follows that an apparent change in BCI_{Ave} score between inspections of less than about 6 points cannot be considered statistically significant. The larger uncertainty in BCI_{Crit} scores means that a change of around 25 points would be required to be significant.

A further consequence of this variation in individual structure BCI scores is that ranking structures by score (especially BCI_{Crit}) in order to prioritise maintenance would produce unreliable results. Thus, it would be undesirable to implement contractual conditions or targets that encourage prioritising interventions purely by structure condition scores.

6.6.3 Uncertainty in BCI scores for stocks of bridges

Given that the computed variation in defect scores does not exhibit significant skew, convergence to the mean dictates that the uncertainty is reduced for metrics that include more data, as is the case for stock-level BCI scores. The sets of plausible scores for each individual structure have been combined into a set of plausible stock level benchmarks by taking the mean of the structure values in each set, weighted by each structure's deck area. The results have been plotted in Figure 6.10. Despite the variation in individual defect scores, the average BCI_{Ave} and BCI_{Crit} scores for the entire stock of structures show very little deviation, with computed standard deviations of 0.06 and 0.20 respectively.

6.7 Concluding remarks

The following concluding remarks are made:

- Significant uncertainty was found in the classification and grading of individual defects during the visual inspection process.
- Defect classifications were particularly inaccurate for common concrete defects, where a large range of possible defect types is available.
- Defect grading by severity and extent was seen to be most unreliable for defects with high extents, and for component types such as *Vehicle Restraint Systems*.
- In the majority of cases, evaluation of testing results did not result in any changes to the defect scores allocated by inspectors following visual inspections.
- The degree of variation in defect grading between inspectors differed between different regional inspection teams, suggesting variation in practice.
- The industry standard *Bridge Condition Indicator* metric was shown to be sensitive to uncertainty in the underlying defect data, with the BCI_{Crit} metric particularly unreliable for comparing the performance of individual structures.

- Use of the *Bridge Condition Indicator* system at stock-level was shown to be considerably more reliable, with low levels of uncertainty.

Chapter 7

Turning Bridge Condition Data into Information

Aspects of this chapter are based on work presented in Bennetts et al. *(2017) and have been reported in Bennetts* et al. *(2018b).*

Bennetts J., Webb G. T. & Denton S. R. (2017) *The State of Bridge Infrastructure. Technical report,* WSP UK ltd on behalf of Highways England

Bennetts J., Webb G. T., Vardanega P. J., Denton S. R. & Loudon N. (2018b) Using data to explore trends in bridge performance. *Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction* **171(1)**: 14–28, 10.1680/jsmic.17.00022

7.1 Introduction

Highways England is responsible for the operation, management and maintenance of England's Strategic Road Network, comprising approximately 21,900 miles of road with 18,500 built structures and carrying more than 85 billion journey miles every year (Highways England, 2014, p. 12,15). As with all bridge owning organisations they collect and store large volumes of data regarding their assets' inventory, condition and maintenance histories. Developing useful information from this data is key to understanding the performance of these assets and providing feedback to inform and improve best practice and standards for bridge design, and operation (UK Roads Liaison Group, 2016).

However, the tools and techniques typically used by practitioners for the analysis and presentation of data are poorly suited to the large volumes of data stored and limited in their capabilities. To address these issues, a structured research programme was developed to provide the evidence and analysis required to allow Highways England to better understand factors influencing the condition of its bridge stock. The rich asset information and intelligence developed in this work will enable Highways England to reduce, better target and better justify its spend on structures maintenance, thus enhancing the value derived from investments made at all stages of a structure's lifecycle and in the structures management information systems used to support decision making.

A significant portion of the the data used in this chapter is based on visual inspection data. The reliabilty of this data is discussed in chapter 6, where it is shown that the aggregation of results to generate the derived metrics used in this chapter reduces the extent to which they are affected by variations in the underlying data, and therefore these metrics can be used to inform decision making at a strategic level.

7.2 Sources of data

7.2.1 Highways England's SMIS database

Highways England holds data on its structures assets, including bridges, on its Structures Management Information System (SMIS) database. The Structures Management Information System comprises a relational database, and is structured with database tables containing static inventory information, and a time-history for events in a structure's lifecycle, such as inspections, recording of new defects, and subsequent treatment of those defects with maintenance actions. The system also includes a simple file-server for documents related to each structure. Due to the complications of the event-based database topography, and challenges in securely accessing the live database, the data for this work was requested as a set of static tables of data in Comma Separated Value (.csv) format. These were produced from the SMIS database by Highways England's IT service providers using scripts written in Structured Query Language (SQL). The specific datasets requested for this work, and provided by Highways England's IT service provider, are set out below.

7.2.1.1 Inventory data

Tables of inventory data were provided covering the full inventory of Bridges and Large Culverts on the network. This data included the full schedule of components that comprise each bridge and information such as the bridge type, maintaining agent, location and construction year. Due to differences in the level of data held on the SMIS database for structures managed as part of Design, Build Finance and Operate (DBFO) arrangements, DBFO managed structures were not included in this study. It was also necessary to remove a small number of structures from the study due to errors identified in their data. In total, data from 7173 of the 8607 bridge records received was included in this study.

7.2.1.2 Current condition data

Bridge Condition Indicator Scores and Element Condition Indicators for each of the Highways England owned (i.e. not including structures managed by DBFO concessionaires) structures on the network were provided. The IT service provider generated scores for each structure at yearly intervals from the 1st April 2006 through to 1st April 2016. Additional outputs of condition scores were also provided during the project on the 1st November and 1st December 2016. Since the defect recording detail level in SMIS changed during this time, the scores from year to year are not necessarily directly comparable.

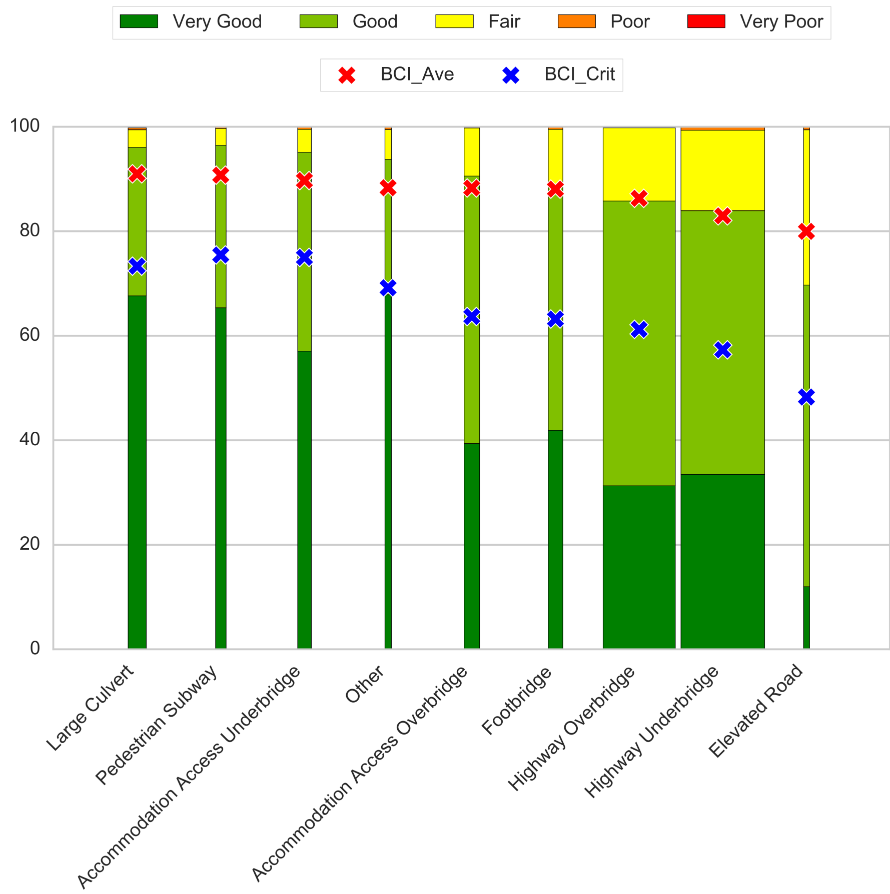

Figure 7.1: Bridge condition split by *structure type*.
Bridge condition split by 'structure type' showing the distribution of average bridge condition indicator scores (BCI_{Ave}) within each category of 'structure type' as percentages falling into the brackets of very poor, poor, fair, good and very good. Also shown are the average BCI_{Ave} and BCI_{Crit} scores for the bridges in each category, which have been weighted by the deck area of each bridge. These scores are on a scale from 0 to 100. The width of the bars has been scaled by the number of bridges in each category.

7.2.1.3 Defect data

Raw defect data was provided by Highways England with defect types, likely cause, severities and extents, as recorded during biennial General Inspections, and six-yearly Principal Inspections. This comprised approximately 500,000 'current' defects, which are yet to be addressed by maintenance actions, and around 3,000,000 historic defect records which have been addressed. Chapter 6 and Bennetts *et al.* (2018a) have demonstrated that, for Highways England's defect data, there is significant uncertainty in the allocation of individual defect scores due to variation between inspectors' opinions during visual inspection. However, these variations become much less significant when considering derived statistics, such as Bridge Condition Indicator scores, for large collections of structures.

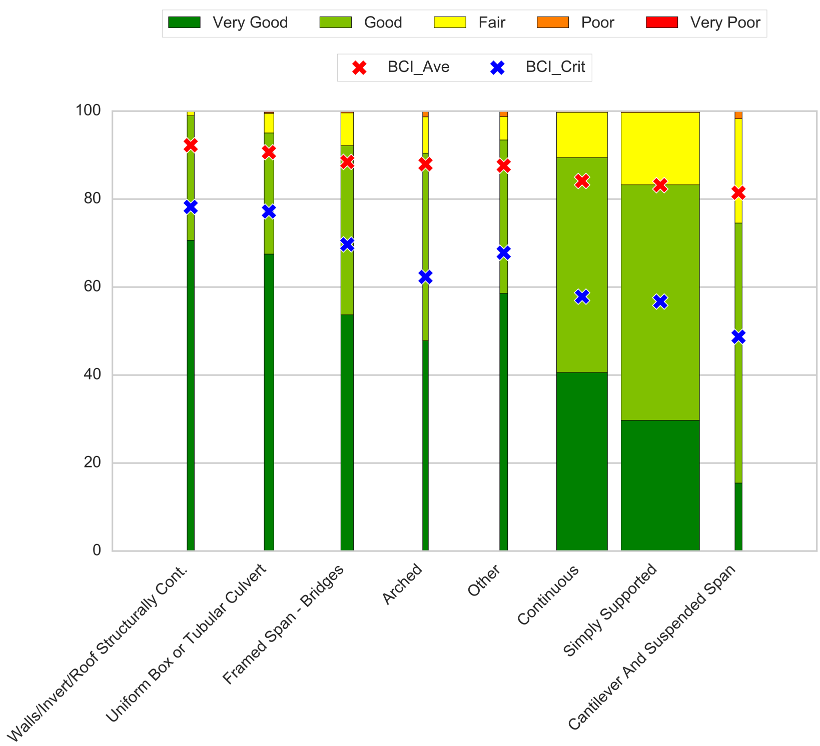

Figure 7.2: Bridge condition split by *deck type*.
Bridge condition split by 'deck type' showing the distribution of average bridge condition indicator scores (BCI_{Ave}) within each category of 'deck type' as percentages falling into the brackets of very poor, poor, fair, good and very good. Also shown are the average BCI_{Ave} and BCI_{Crit} scores for the bridges in each category, which have been weighted by the deck area of each bridge. These scores are on a scale from 0 to 100. The width of the bars has been scaled by the number of bridges in each category.

7.2.2 Data from Benchmark Inspections

Experienced bridge inspectors from WSP Ltd observed 200 Principal Inspections on Highways England's network between 2014 and 2017, and were asked to complete a report for each structure. The study details, sample selection and processing is discussed in detail in Chapter 6.

7.3 Analysis tools and methods

7.3.1 Data analysis environment

A suite of scripts was developed to analyse the project's quantitative data and present results in the form of statistics and plots. These tools were used to calculate element, bridge and stock level Bridge

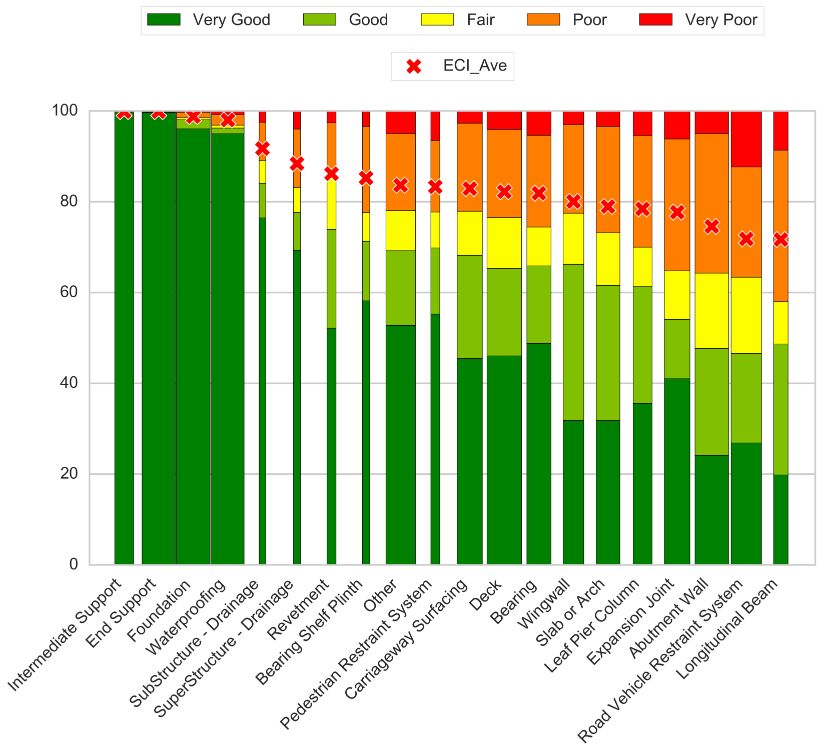

Figure 7.3: Element condition, split by *element type*.
Element condition split by element type showing the distribution of average element condition indicator scores (ECI_{Ave}) within each category of element type as percentages falling into the brackets of very poor, poor, fair, good and very good. Also shown is the average of the element condition indicator scores for each element type. These scores are on a scale from 0 to 100. The width of the bars has been scaled by the number of elements in each category, such that categories that represent only a small number of elements can be readily identified.

Condition Scores from the raw inventory and defect data and also to evaluate changes over time. More complex tools were also developed to identify multi-factor trends by adopting the machine learning algorithms used to build Optimal Decision Trees to build Importance Dendrograms. The majority of these tools were developed in Python 3.x, making use of features from the Python toolkits scheduled in chapter 3.

7.3.2 Quantifying bridge condition

Condition scores (BCI_{Ave} and BCI_{Crit}), which are defined in detail in Chapter 6, have been calculated for each individual bridge according to the Bridge Condition Indicator system (Sterritt & Shetty, 2002), with slight modifications to align with the SMIS recording format as set out in Section 2.4.3.

7.3.3 Analysis of the change in condition with time

SMIS condition score reports were obtained for each year between 2006 and 2016, with the intention of allowing any changes in the condition of bridges and their components over time to be investigated. However, the recording of inspections was gradually migrated from the BE11 format to the current SMIS format between 2007 and 2016. Condition scores calculated using the two different inspection formats are not directly comparable, partly due to the increased level of detail recorded with the SMIS format - defects are now recorded on individual components, such as individual bearings or beams, rather than groups of components. Therefore, it is not meaningful to plot the condition of the stock over time for the full 10 years of available data. However, there are some structures which have now had two Principal Inspections under the new inspection and recording regime, allowing comparisons to be made. There are not significant numbers of structures available for comparison until 2007 and therefore, with the 6-year cycle of the PI programme, comparisons could only be made for 4 successive years. In each case, the first inspection was the year in which the structure was 'migrated' to the new SMIS inspection reporting format (Figure 7.4). For example, the cohort of structures labelled as '2007' was selected to consist of all the bridges which were migrated to the SMIS recording style in 2007 and had Principal Inspections in 2007 and 2013. Using the data available, it was possible to select three further cohorts of structures migrated to the new system in 2008, 2009 and 2010 and re-inspected in 2014, 2015 and 2016 respectively.

Comparison of condition between two Principal Inspections was possible for a total of 2,379 bridges, the breakdown by year is presented in Table 7.1. Comparisons of the condition of individual elements between inspections was possible for these structures, with a total of 25,472 element conditions compared.

Table 7.1: Summary of the number of bridges and components included in each comparison cohort. Data provided by Highways England

	Comparison cohort			
	2007 - 2013	2008 - 2014	2009 - 2015	2010 - 2016
Number of bridges	112	830	1076	361
Number of components	999	8014	12254	4205

The conditions of these populations of bridges are plotted as the average BCI_{Crit} and BCI_{Ave} scores for the population, weighted by deck area in Figure 7.4. Each marker has been coloured to indicate the pair-wise comparison to which it relates, labelled by the first inspection in the comparison. Considering that the 2007 cohort is a smaller group of structures, and appears to have performed worse than the later cohorts of bridges, it appears likely that these results could be unrepresentative of the general trend, possibly due to some bias in the structures that were chosen for migration in the first year.

7.3.4 Deterioration rates

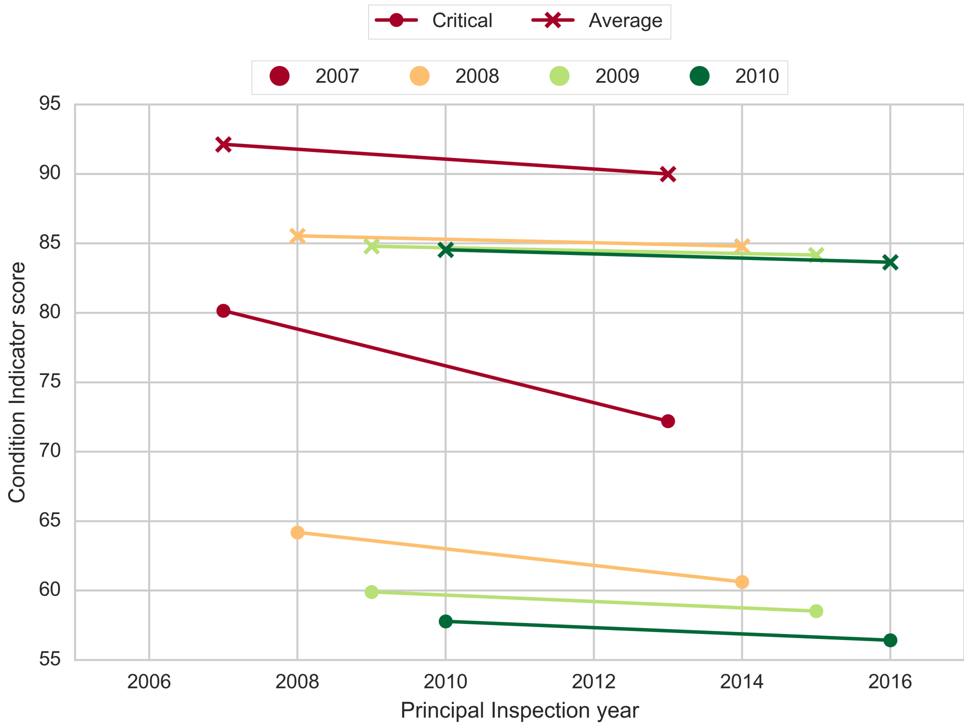

Figure 7.4: Change in condition over time for the whole stock.
Change in condition between successive inspections for populations of structures that were inspected in the same year. The conditions of these populations of bridges are plotted as the average BCI_{crit} and BCI_{Ave} scores for the population, weighted by deck area. A total of 2397 bridges are included in this plot.

In addition to analysing changes in the condition of the whole bridge stock it was also possible to consider the changes in condition of particular sub-populations of structures by characteristics such as 'structure type', 'construction material' or obstacle crossed. This allowed deterioration rates for different types of structures to be estimated. For each structure the rate of change of condition score (for both average and critical scores) was estimated from the difference in score between two successive Principal Inspections i.e. over a 6-year time interval. Within each sub-population, the changes in average BCI_{Ave} and BCI_{Crit} scores (weighted by deck area) were then calculated.

Figure 7.4 shows some differences between the performances of the different cohorts of structures. There is a possibility that this may be an artefact of the dates on which structures in different areas were migrated from BE11 to SMIS. For this reason, data from each of the four cohorts of structures have been plotted as separate markers. The weighted average of the four years is plotted as a black bar. It is noted that while some data points from 2007 appear anomalous, no cause could be attributed to this, and they do not significantly affect the location of the average. The size of each marker has been scaled by the number of bridges that it represents, such that outliers that only represent a small number of bridges can be readily identified.

7.3.5 Use of importance dendrograms to identify multi-factor trends

Given the categorical nature and large number of attributes that can affect the performance of bridge structures, the heterogeneous nature of the UK's bridge stock, and the potential for multi-factor associations, it is not clear from standard data analysis techniques such as simple linear regression, what the most influential variables are and whether there are particularly informative trends associated with specific sub-populations of bridges. For example, it would be difficult to identify in a structured way if there were a particular issue with the performance of a given type and age of bridge in a specific region of the network. To provide this structured methodology for identification of the most informative multi-factor trends in both the condition and rate of change of condition of Highways England's stock of bridges, an optimal decision tree machine learning method has been adopted as a form of data-mining to derive hierarchical trees representing the most influential factors affecting current bridge condition and the rate of change of condition. These trees have been rendered as 'Importance Dendrograms', graphically displaying the trends in bridge condition and rate of change in condition by categorical factors such as 'construction type' or 'region' for Highways England's stock of bridges. Futher detail on the Optimal Decision Tree algorithm and its use to render Importance Dendrograms is presented in Section 3.4.

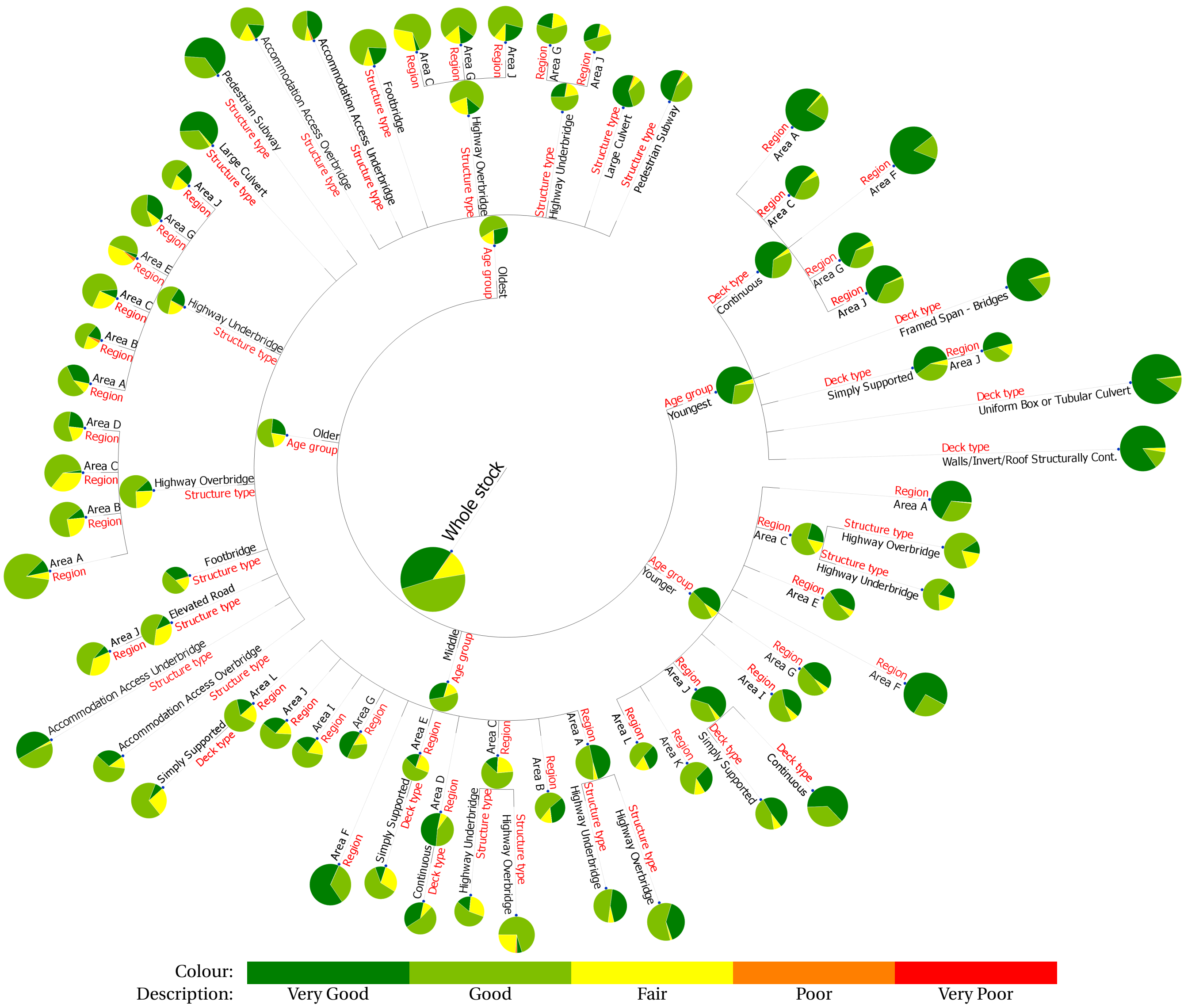

Figure 7.5: Importance dendrogram for bridge condition.
Importance dendrogram showing the most informative multi-factor trends in Average Condition score (BCI_{Ave}). The condition of the bridges has been banded from Very Good to Very Poor. Each pie chart represents the distribution of the condition bandings within the sub-population below that point in the tree structure. The top 'Whole stock' pie-chart represents the distribution of condition in the whole stock. The red text on each branch of the tree represents the attribute that the dataset has been partitioned by at that level, and the black text represents the value of the attribute. The size of each node (pie-chart) has been drawn inversely proportional to its entropy, such that the most informative partitions can be readily identified.

7.3.5.1 Details of parameters used to derive importance dendrogram for condition

To generate the importance dendrogram for current condition (figure 7.5), the following attributes were given to the algorithm from which it selected the optimum tree topology: *structure type*, *construction type*, *deck type*, *structure use*, *distance from coast*, *region*, and *age group*. *Age group* splits the bridges into five bands from youngest to oldest with the same number of bridges in each band. *Region* splits the bridges into the 14 'Maintenance Areas' into which the Network is divided for the purposes of letting contracts for the maintenance and inspection of portions of the network. The names of the maintenance areas have been anonymised. Nodes, and corresponding branches, have only been drawn if they represent at least 35 bridges. The depth of the dendrogram was limited to 3 partitions.

7.3.5.2 Details of parameters used to derive importance dendrogram for change in condition

The following attributes were given to the algorithm from which it selected the optimum tree topology for change in bridge condition (presented in figure 7.11): *structure type, construction type, deck type, structure use, distance from coast, region, age group*, BCI_{Ave}, and *comparison year*. Where BCI_{Ave} splits the bridges into five bands by their BCI_{Ave} condition score, from best to worst. Comparison year is the inspection year in which the first of the two compared sequential Principal Inspections took place.

7.4 Results

7.4.1 Trends in bridge condition

The overall condition of Highways England's stock (n = 7173, excluding structures managed by DBFO contractors) is presented in Table 7.2. Overall, the vast majority of the bridge stock was found to be in either 'Very Good' or 'Good' condition.

Table 7.2: Stock level condition scores for all bridges on Highways England's network

			Condition Bandings				
Count	BCI_{Ave}	BCI_{Crit}	Very Good	Good	Fair	Poor	Very Poor
7173	84.1	58.2	39.50%	47.80%	12.30%	0.40%	0.00%

Figures 7.1 and 7.2 show the condition of Highways England's bridge stock, grouped by *structure type* and *deck type*. Figure 7.3 presents the current condition (ECI_{Ave}) of elements on the network, split by component type. Figure 7.5 demonstrates that, of the factors considered, structure age has the biggest effect on the condition of a bridge, followed in most cases by *structure type* and *deck type*.

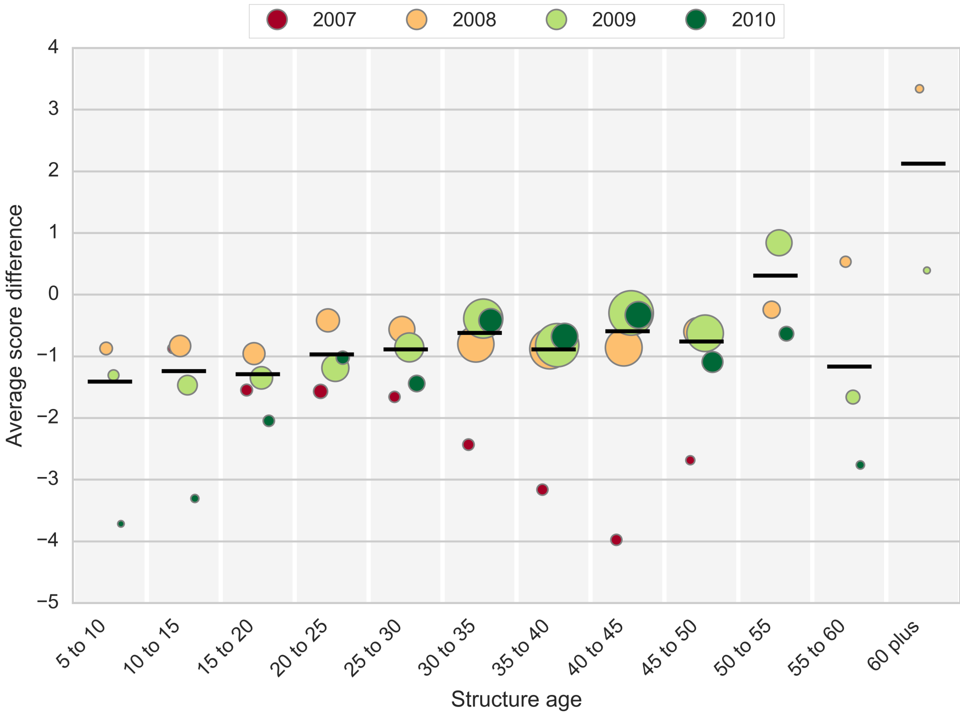

Figure 7.6: Deterioration in BCI_{Ave} split by *structure age*.
Deterioration rate plots showing the change in BCI_{Ave} between successive inspections for populations of structures that were inspected in the same year, split by *structure age* . The change of condition with time of these populations of bridges has been plotted as the difference between the average of the BCI scores for the population in each of the successive inspections, weighted by deck area to account for the relative importance of larger structures. The markers have been shaded to indicate the comparison year. The size of the marker has been scaled by the number of bridges that it represents. The weighted average of the plotted comparison years has been plotted on the top as a black bar. Data from 2397 bridges is included in this plot.

7.4.2 Trends in change in bridge condition

Figure 7.4 shows that the condition of Highways England's stock on the whole is relatively static, with a slow rate of deterioration over the study period. Figures 7.6, 7.7, 7.8, 7.9 show how the rate of change of condition varies as a function of bridge age and type.

Figure 7.11 shows that the most informative factor in the rate of change of condition is a structure's current condition. Counter-intuitively, structures in better condition have deteriorated faster, while those in a poorer condition appear to have deteriorated more slowly. The maintenance region and the structure type are also influential in the rate of deterioration.

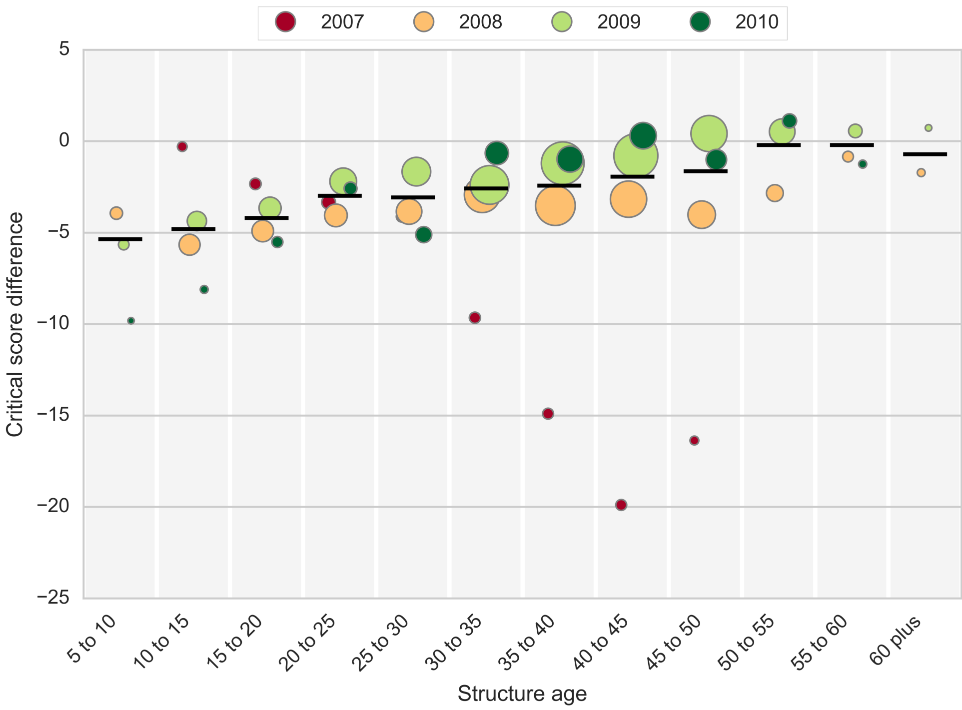

Figure 7.7: Deterioration in BCI_{Crit} split by *structure age*.
Deterioration rate plots showing the change in BCI_{Crit} between successive inspections for populations of structures that were inspected in the same year, split by *structure age*. The change of condition with time of these populations of bridges has been plotted as the difference between the average of the BCI scores for the population in each of the successive inspections, weighted by deck area to account for the relative importance of larger structures. The markers have been shaded to indicate the comparison year. The size of the marker has been scaled by the number of bridges that it represents. The weighted average of the plotted comparison years has been plotted on the top as a black bar. Data from 2397 bridges is included in this plot.

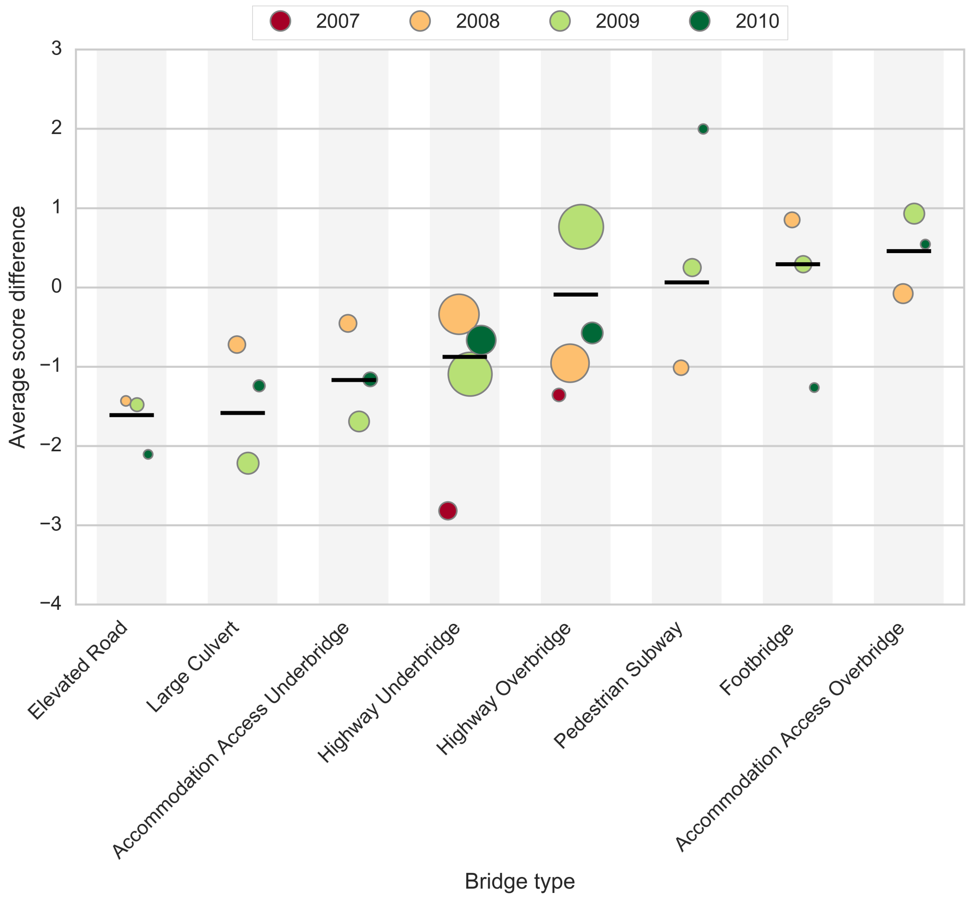

Figure 7.8: Deterioration in BCI_{Ave} split by *bridge type*.
Deterioration rate plots showing the change in BCI_{Ave} between successive inspections for populations of structures that were inspected in the same year, split by *bridge type*. The change of condition with time of these populations of bridges has been plotted as the difference between the average of the BCI scores for the population in each of the successive inspections, weighted by deck area to account for the relative importance of larger structures. The markers have been shaded to indicate the comparison year. The size of the marker has been scaled by the number of bridges that it represents. The weighted average of the plotted comparison years has been plotted on the top as a black bar. Data from 2397 bridges is included in this plot.

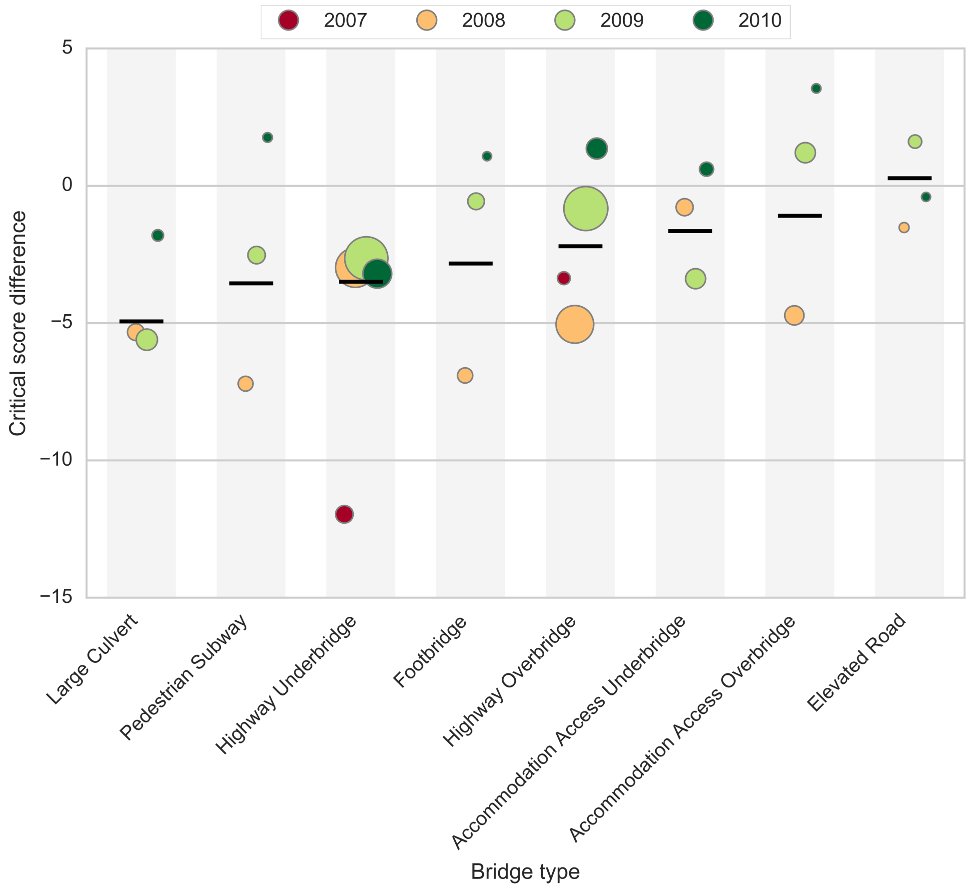

Figure 7.9: Deterioration in BCI_{Crit} split by *bridge type*.
Deterioration rate plots showing the change in BCI_{Crit} between successive inspections for populations of structures that were inspected in the same year, split by *bridge type*. The change of condition with time of these populations of bridges has been plotted as the difference between the average of the BCI scores for the population in each of the successive inspections, weighted by deck area to account for the relative importance of larger structures. The markers have been shaded to indicate the comparison year. The size of the marker has been scaled by the number of bridges that it represents. The weighted average of the plotted comparison years has been plotted on the top as a black bar. Data from 2397 bridges is included in this plot.

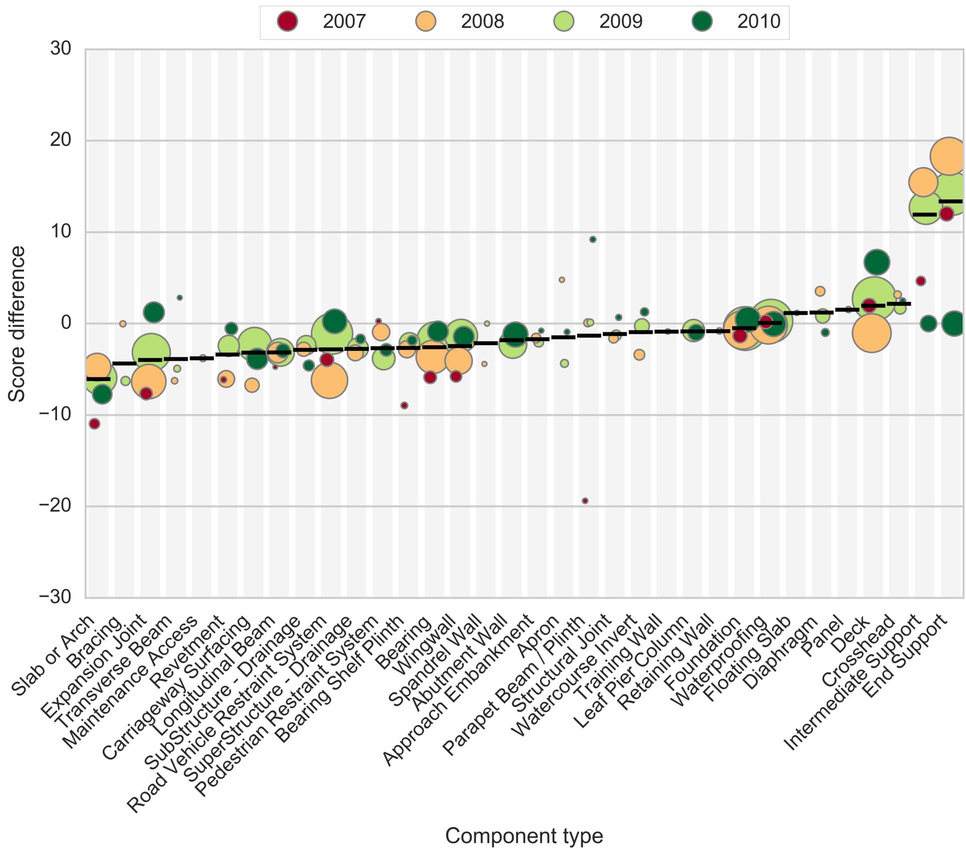

Figure 7.10: Change in component condition by component type.
Change in condition between successive inspections for populations of components that were inspected in the same year. These ECI scores have been split by *component type* to show differences in the rate of deterioration. The change of condition with time of these populations of components has been plotted as the difference between the average of the ECI scores for the population in each of the successive inspections.The markers have been shaded to indicate the comparison year (by the first year of the pair-wise comparison). The size of the marker has been scaled by the number of components that it represents, such that outliers that only represent a small number of bridges can be readily identified. Markers have only been drawn where they represent 10 or more components. The weighted average of the plotted comparison years has been plotted on the top as a black bar.

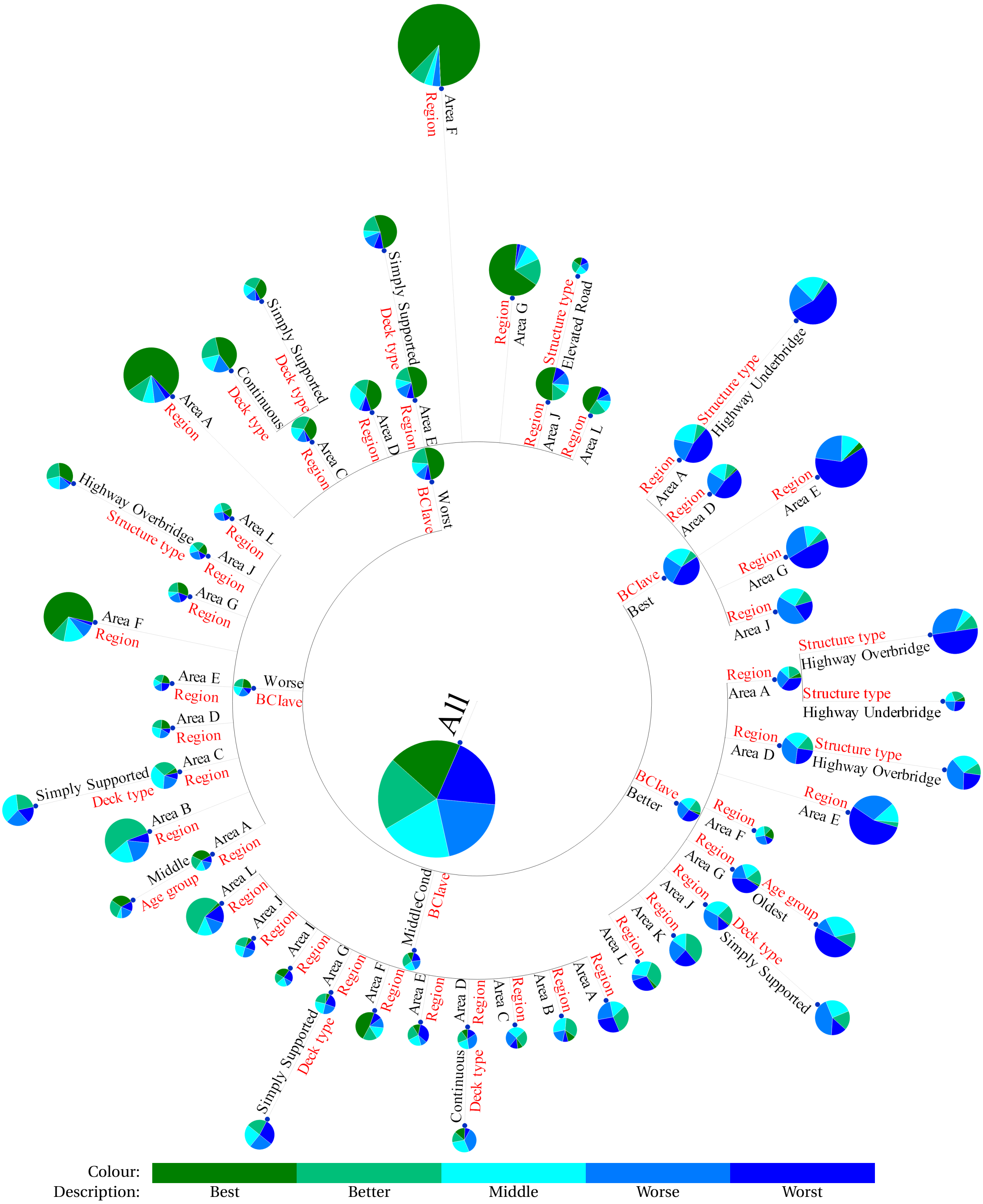

Figure 7.11: Importance dendrogram for change in condition.
Importance dendrogram showing the most informative multi-factor trends in change in Average Condition score BCI_{Ave}. The change in condition of the bridges between two consecutive Principal Inspections has been banded from Best to Worst using an even split into five bandings with the same number of bridges in each. Each pie chart represents the distribution of the condition change bandings within the sub-population below that point in the tree structure. The top 'All' pie-chart represents the distribution of change in condition in the full population of bridges for which direct comparisons could be made. The red text on each branch of the tree represents the attribute that the dataset has been partitioned by at that level, and the black text represents the value of the attribute.

7.4.3 Trends in construction quality

7.4.3.1 Construction issue defects

For defects which have a significant enough extent or severity score (Highways England, 2018) inspectors are also asked to record the cause of the defect. Of currently valid defects which have a cause recorded, 9% of those defects were recorded as being due to construction issues. Figures 7.12 to 7.17 show the distribution of these construction issue defects by type, component, construction year and maintaining agent.

The variation in the number of construction defects with structure age can be broken down further into the different defect types. The historic trends in different construction issue defects have been classified as follows:

- Defect types that appeared to be **decreasing** in prevalence with time.
- Defect types that appeared to be **increasing** in prevalence with time.
- Defect types that appeared to be prevalent in old structures and new structures, but were less prevalent in structures within an intermediate age range of approximately 10 to 30 years.
- Defect types that did not appear to exhibit any trend.

The following defect types appeared to be **decreasing** in prevalence with time:

- Construction joint cracks.
- Degraded components.
- Exposed Reinforcement
- Broken or fractured components.
- Defects related to repairs and failed repairs although it is not immediately clear why these should be classified as construction defects.
- Hollow (delaminated) areas.
- Poor compaction.
- Plastic shrinkage cracks
- Reinforcement corrosion crack Similar to exposed reinforcement, this could be related either to the amount of time that it takes for sufficient corrosion of reinforcement to occur to lead to cracking, or to improvements in construction quality.
- Defects related to Rusty nails / Tie wire.

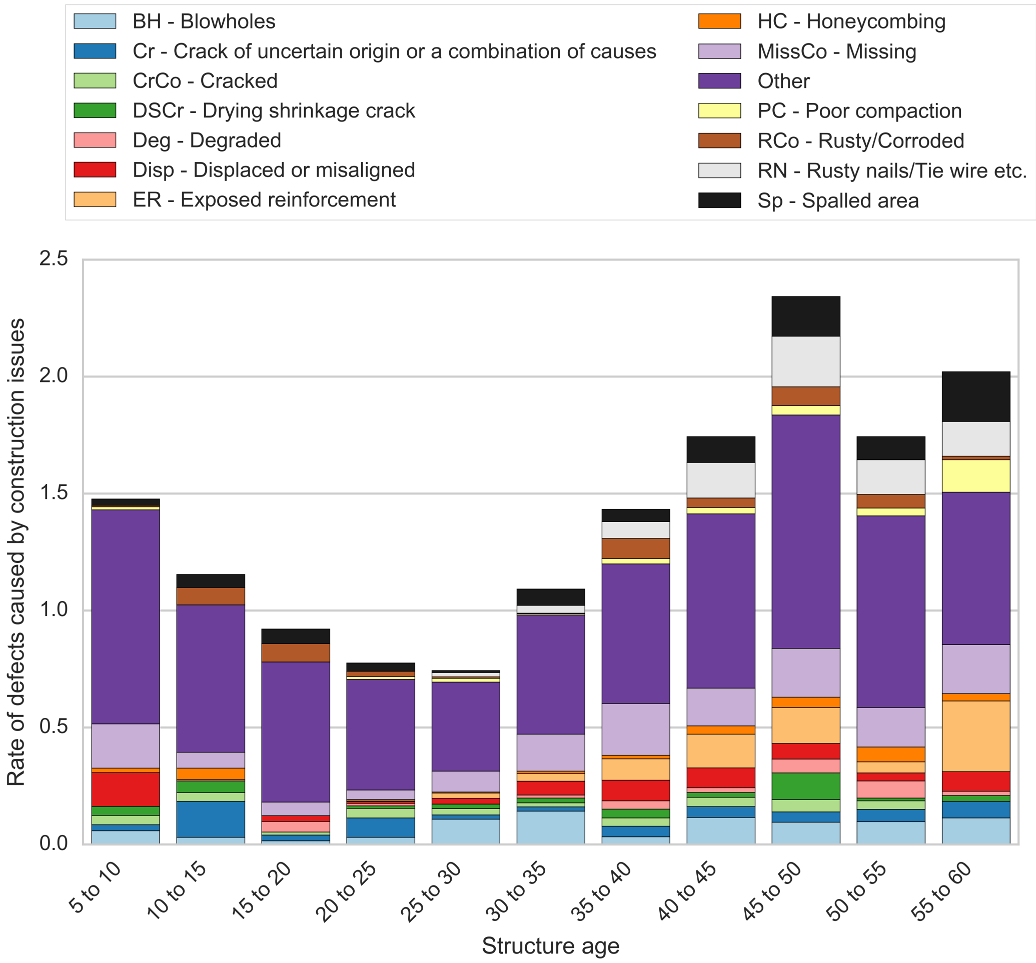

Figure 7.12: Variation in type of defects caused by construction issues with structure age, shown as defect rate per structure.
This plot shows the variation in the number of recorded construction defects with structure age, with bars coloured by the recorded defect type. The height of each bar indicates the average number of construction defects per structure of each defect type within each age group. The 'Other' category includes all defect types for which there are fewer than 200 recorded construction defects.This plot has been produced from a download of raw defect data from SMIS obtained in February 2017 containing all currently valid defects. Structure age has been calculated from November 2016. Where defects in SMIS have been applied to multiple components these have each been counted individually.

- Spalled areas.
- Defects related to running water.

The following defect types appeared to be increasing in prevalence with time:

- Cracks of uncertain origin.
- Cases of debris or rubbish on or adjacent to the structure.
- Iron pyrites stains.
- Lack of fill over or adjacent to structures.
- Blistering.
- Rusting or rust staining from substrate.
- White deposits.

The following defect types appeared to be prevalent in both old and new structures with a reduction in rate within an intermediate age range:

- Blowholes.
- Poorly installed connectors.
- Displaced or misaligned components.
- Honeycombing.
- Defects related to irregular shuttering have been most frequently recorded for structures aged 45 to 50 years and 5 to 10 years.
- The rate of defects relating to missing components was fairly constant although there was a noticeable reduction for structures aged between about 10 and 30 years.
- Rusty / corroded components.

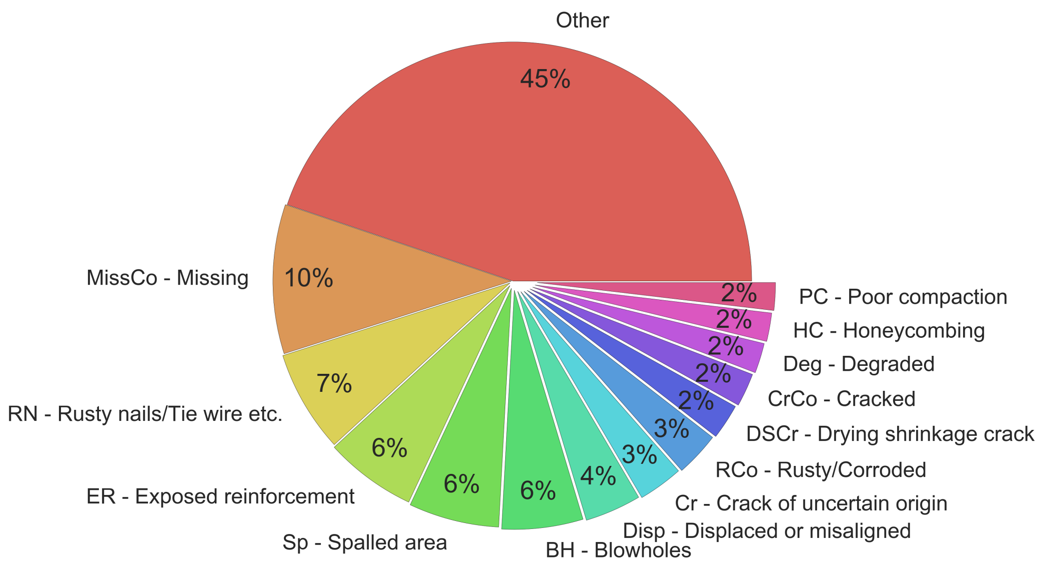

Figure 7.13: Recorded defect type for all defects caused by construction issues.
Recorded defect type for all defects in SMIS which are recorded to be caused by construction issues. The 'Other' category includes all defect types for which there are fewer than 200 recorded defects. This plot has been produced from a download of raw defect data from SMIS obtained in February 2017 containing all currently valid defects. Where defects in SMIS have been applied to multiple components these have each been counted individually.

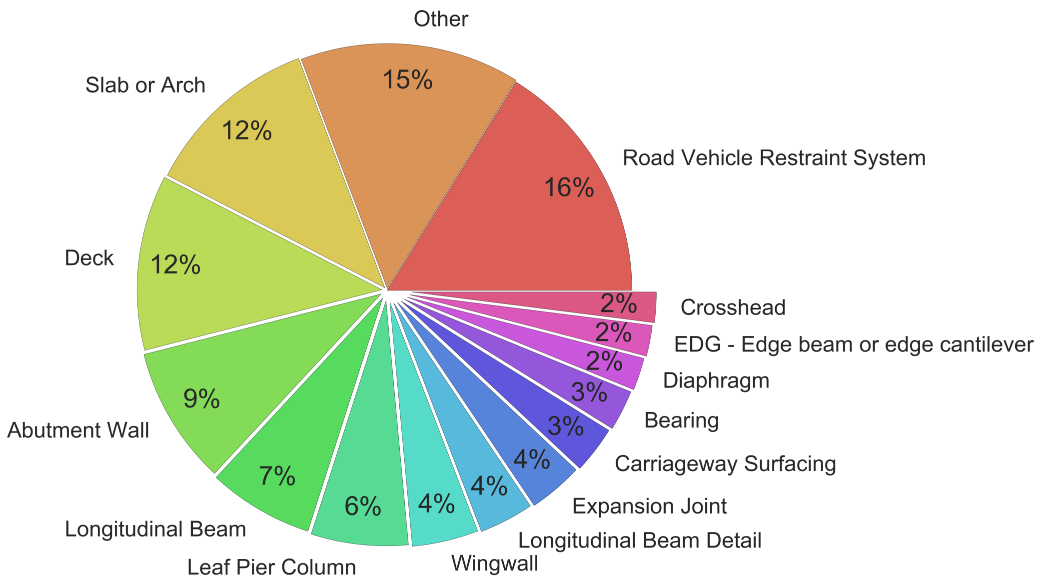

Figure 7.14: Recorded component type for all defects caused by construction issues.
Recorded component type for all defects in SMIS which are recorded to be caused by construction issues. The 'Other' category includes all component types for which there are fewer than 200 recorded defects. This plot has been produced from a download of raw defect data from SMIS obtained in February 2017 containing all currently valid defects. Where defects in SMIS have been applied to multiple components these have each been counted individually.

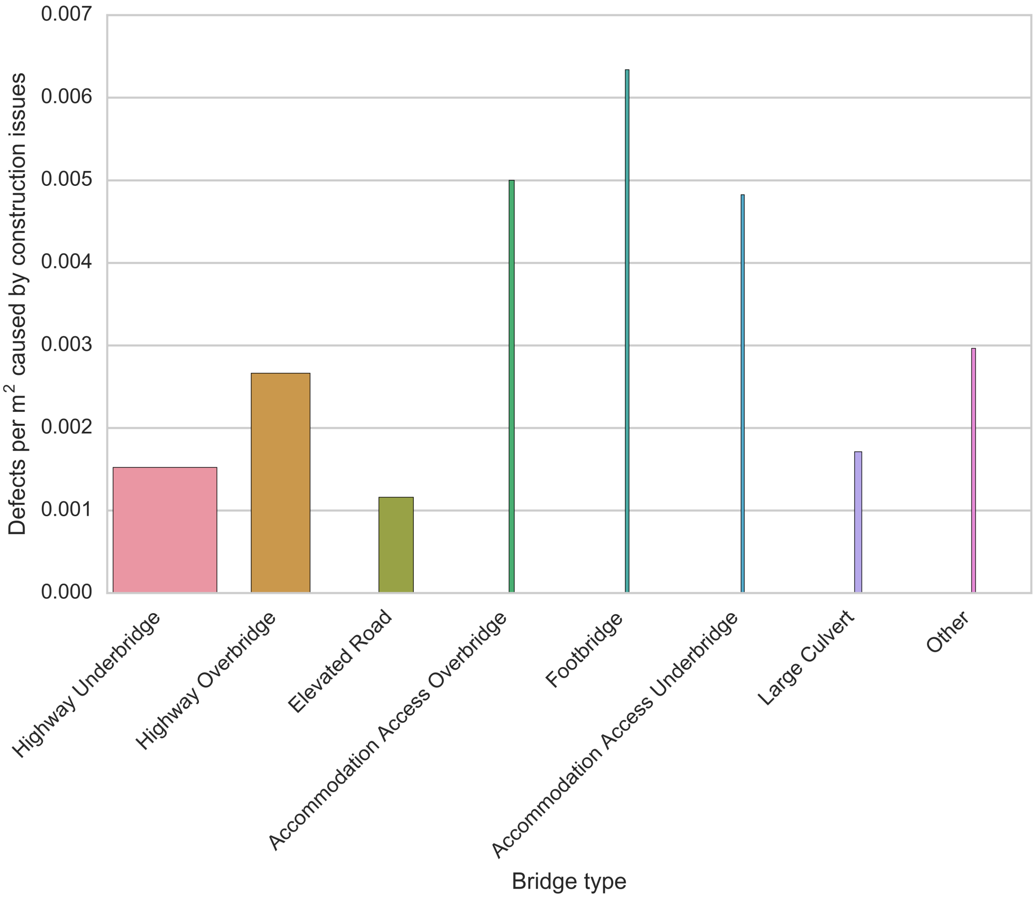

Figure 7.15: Variation in rate of construction defects per square metre of deck with bridge type.
This plot shows the variation in the number of recorded construction defects with bridge type. The average number of defects per square metre of deck is plotted for each bridge type.The widths of the bars have been scaled by the total deck area of structures in each category, such that categories that represent only a small proportion of structures can be readily identified. This plot has been produced from a download of raw defect data from SMIS obtained in February 2017 containing all currently valid defects. Where defects in SMIS have been applied to multiple components these have each been counted individually.

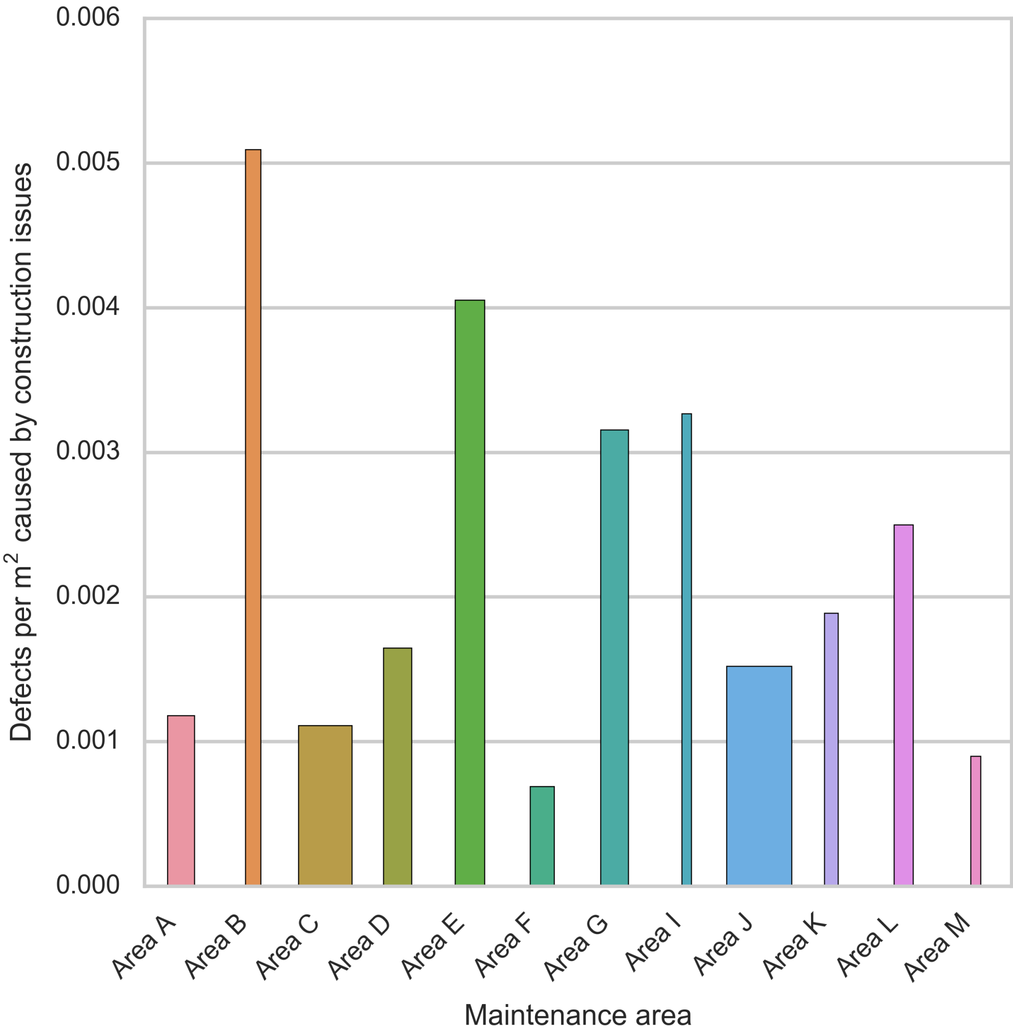

Figure 7.16: Variation in rate of construction defects per square metre of deck with maintenance area. This plot shows the variation in the number of recorded construction defects with maintenance area. The average number of defects per square metre of deck is plotted for each maintenance area. The widths of the bars have been scaled by the total deck area of structures in each category, such that categories that represent only a small proportion of structures can be readily identified. This plot has been produced from a download of raw defect data from SMIS obtained in February 2017 containing all currently valid defects. Where defects in SMIS have been applied to multiple components these have each been counted individually.

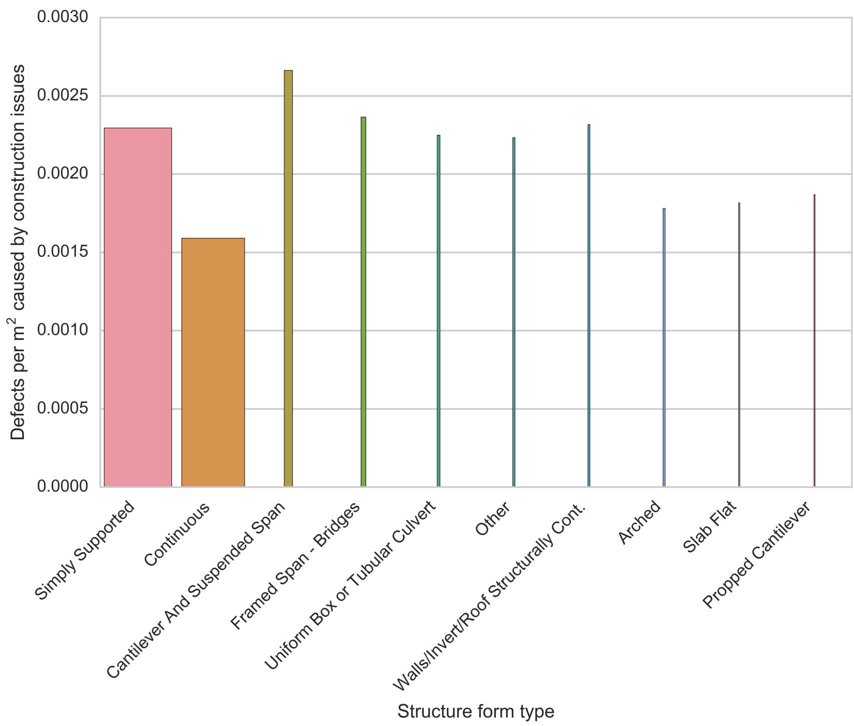

Figure 7.17: Variation in rate of construction defects per square metre of deck with structure form type.
This plot shows the variation in the number of recorded construction defects with structure form type. The average number of defects per square metre of deck is plotted for each *structure form type. The widths of the bars have been scaled by the total deck area of structures in each category, such that categories that represent only a small proportion of structures can be readily identified. This plot has been produced from a download of raw defect data from SMIS obtained in February 2017 containing all currently valid defects. Where defects in SMIS have been applied to multiple components these have each been counted individually.

7.4.3.2 Evidence of poor quality construction noted during Benchmark Inspections

During the Benchmark Inspections, WSP's inspectors were asked to comment on any evidence of poor quality construction. Relevant extracts from each Benchmark Inspection have been subjectively scored on a scale of 0 to 5, where 0 indicates no evidence of poor quality construction and 5 indicates strong evidence. These scorings are presented in Figures 7.18 to 7.22, grouped by different categories.

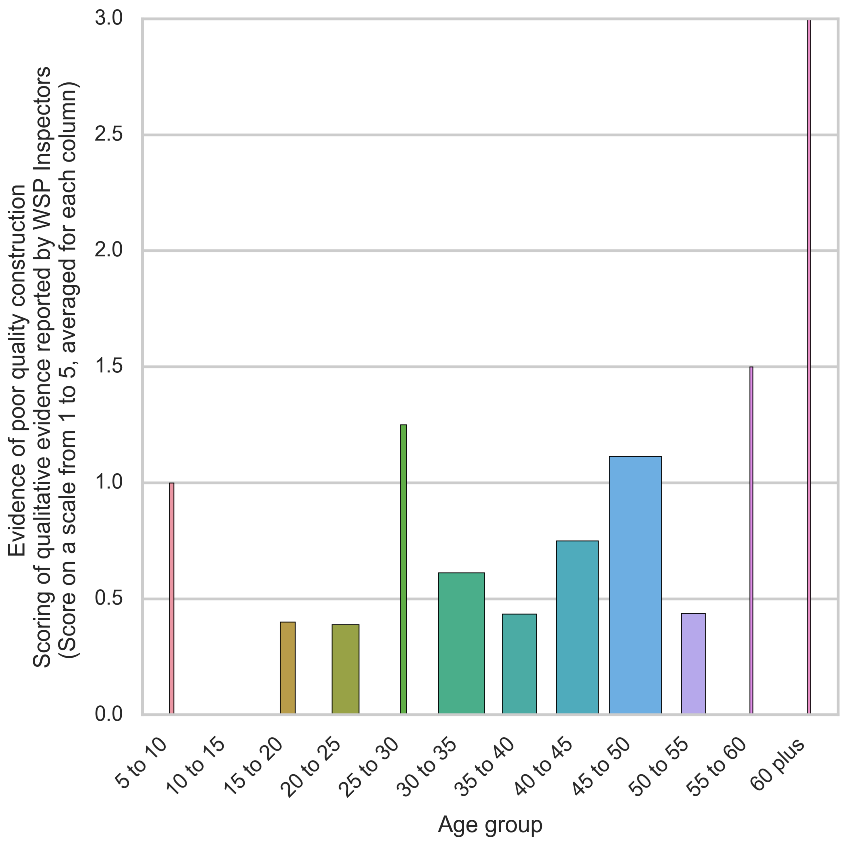

Figure 7.18: Evidence of poor quality of construction by age group.
This plot of qualitative weightings applied to codes in Dedoose.com, shows the average scores applied on a scale from 0-5 for evidence of poor quality of construction, split into categories of age group. Only one weighted code per structure in the sample of 200 has been included, with the most critical taken if there was more than one weighted code for evidence of poor quality of construction applied to a Benchmark Inspection report. The weighted codes were applied subjectively to extracts of text from the Benchmark Inspection reports, where the WSP inspector that witnessed the Benchmark Inspection recorded comments and observations that provide evidence to give judgement on evidence of poor quality of construction. The widths of the bars have been scaled to indicate the number of codes (taking only one per Benchmark Inspection report) applied to each category of age group. The categories are displayed in order of age group.

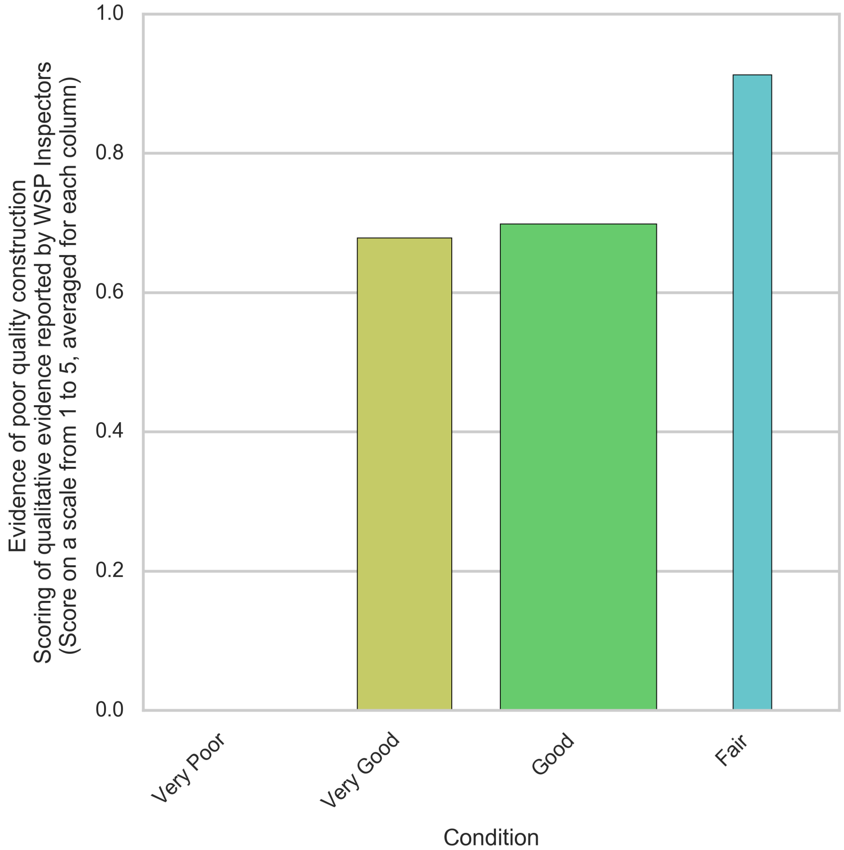

Figure 7.19: Evidence of poor quality of construction by condition.
This plot of qualitative weightings applied to codes in Dedoose.com, shows the average scores applied on a scale from 0-5 for evidence of poor quality of construction, split into categories of condition. Only one weighted code per structure in the sample of 200 has been included, with the most critical taken if there was more than one weighted code for evidence of poor quality of construction applied to a Benchmark Inspection report. The weighted codes were applied subjectively to extracts of text from the Benchmark Inspection reports, where the WSP inspector that witnessed the Benchmark Inspection recorded comments and observations that provide evidence to give judgement on evidence of poor quality of construction. The widths of the bars have been scaled to indicate the number of codes (taking only one per Benchmark Inspection report) applied to each category of condition. The categories are displayed in order of average applied weight.

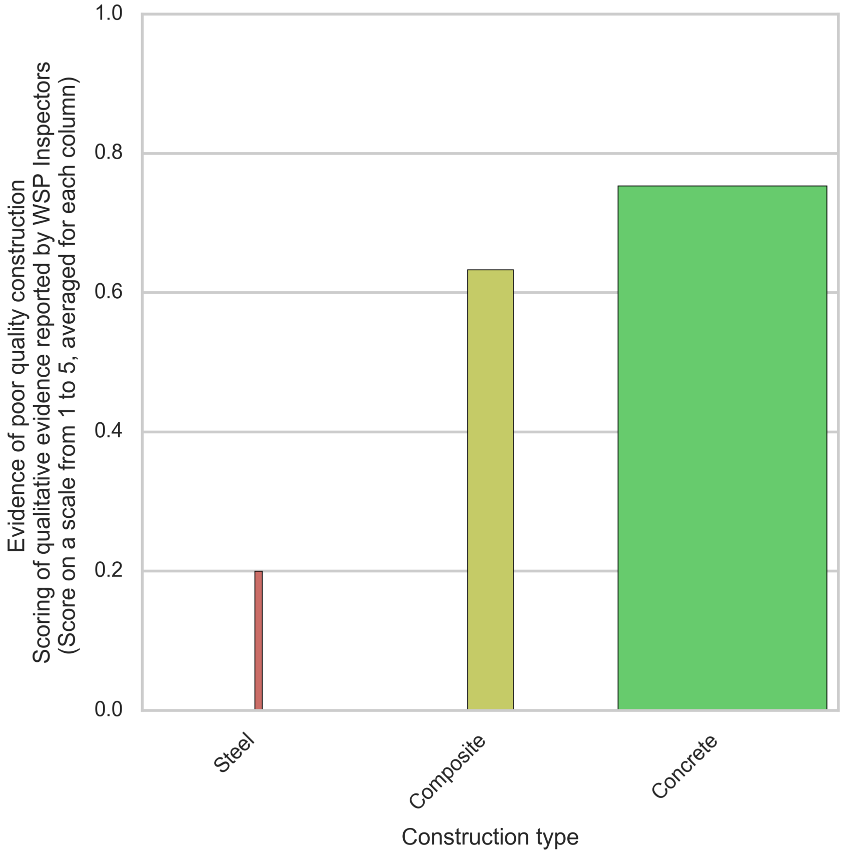

Figure 7.20: Evidence of poor quality of construction by construction type.
This plot of qualitative weightings applied to codes in Dedoose.com, shows the average scores applied on a scale from 0-5 for evidence of poor quality of construction, split into categories of construction type. Only one weighted code per structure in the sample of 200 has been included, with the most critical taken if there was more than one weighted code for *evidence of poor quality of construction* applied to a Benchmark Inspection report. The weighted codes were applied subjectively to extracts of text from the Benchmark Inspection reports, where the WSP inspector that witnessed the Benchmark Inspection recorded comments and observations that provide evidence to give judgement on evidence of poor quality of construction. The widths of the bars have been scaled to indicate the number of codes (taking only one per Benchmark Inspection report) applied to each category of construction type. The categories are displayed in order of average applied weight.

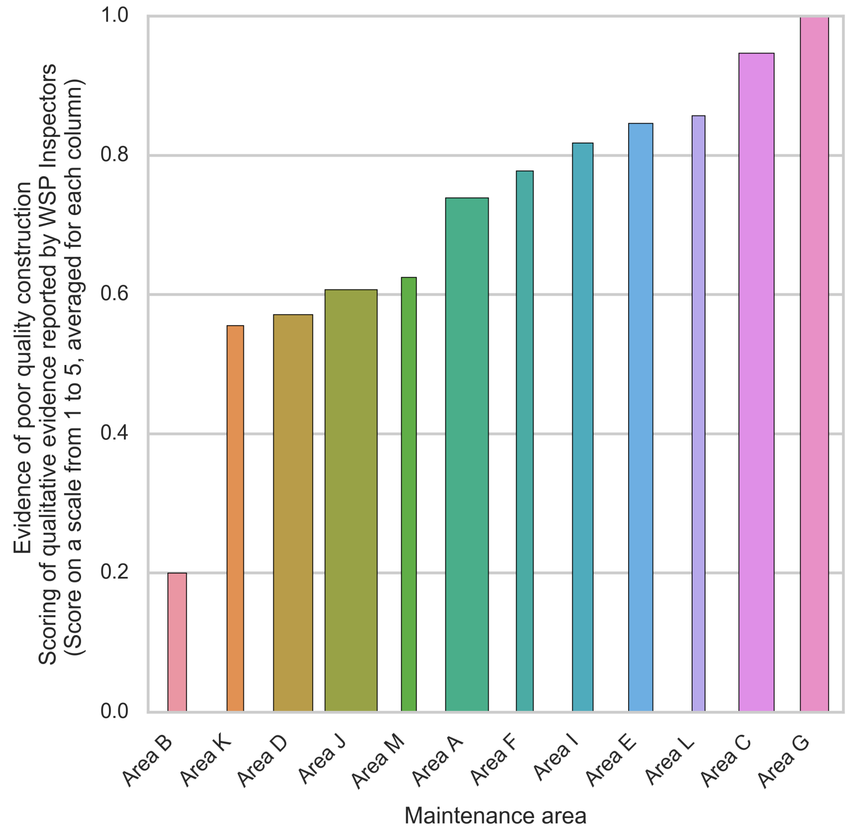

Figure 7.21: Evidence of poor quality of construction by maintenance area.
This plot of qualitative weightings applied to codes in Dedoose.com, shows the average scores applied on a scale from 0-5 for evidence of poor quality of construction, split into categories of structure type. Only one weighted code per structure in the sample of 200 has been included, with the most critical taken if there was more than one weighted code for evidence of poor quality of construction applied to a Benchmark Inspection report. The weighted codes were applied subjectively to extracts of text from the Benchmark Inspection reports, where the WSP inspector that witnessed the Benchmark Inspection recorded comments and observations that provide evidence to give judgement on evidence of poor quality of construction. The widths of the bars have been scaled to indicate the number of codes (taking only one per Benchmark Inspection report) applied to structures in each maintenance area. The Areas are displayed in order of average applied weight.

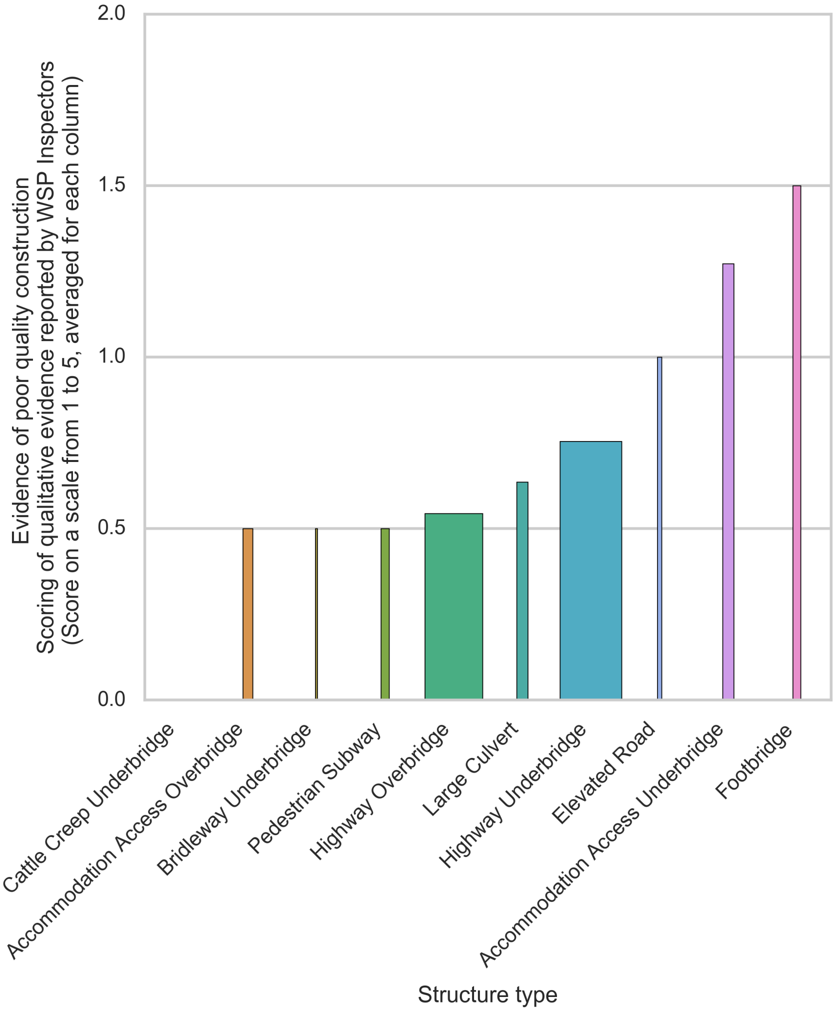

Figure 7.22: Evidence of poor quality of construction by structure type.
This plot of qualitative weightings applied to codes in Dedoose.com, shows the average scores applied on a scale from 0-5 for evidence of poor quality of construction, split into categories of structure type. Only one weighted code per structure in the sample of 200 has been included, with the most critical taken if there was more than one weighted code for evidence of poor quality of construction applied to a Benchmark Inspection report. The weighted codes were applied subjectively to extracts of text from the Benchmark Inspection reports, where the WSP inspector that witnessed the Benchmark Inspection recorded comments and observations that provide evidence to give judgement on evidence of poor quality of construction. The widths of the bars have been scaled to indicate the number of codes (taking only one per Benchmark Inspection report) applied to each category of structure type. The categories are displayed in order of average applied weight.

7.4.4 Trends in water management

On the Benchmark Inspection Record sheets WSP's inspectors were asked to record evidence of whether bridge designs adequately consider water management and to comment on both the performance of water management and the adequacy of any maintenance to water management. These responses have been rated qualitatively on a scale from 0 for inadequate water management to 5 for excellent performance. A selection of resulting scorings are presented graphically in Figures 7.23 to 7.25.

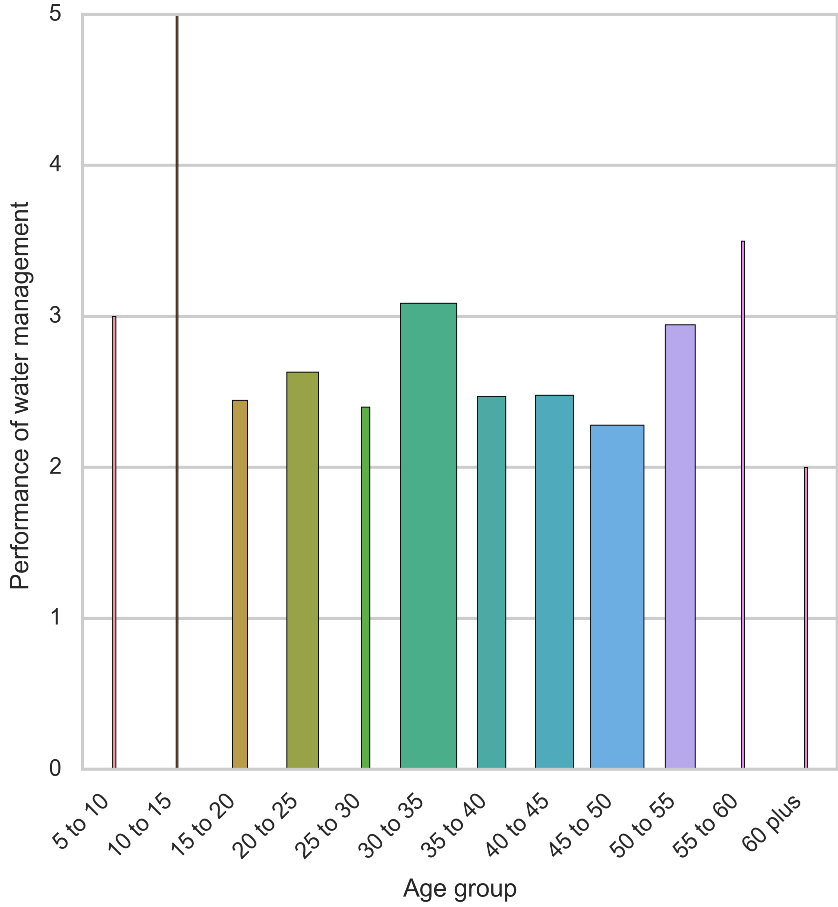

Figure 7.23: Performance of water management by age group.
This plot of qualitative weightings applied to codes in Dedoose.com, shows the average scores applied on a scale from 0-5 for performance of water management, split into categories of age group. Only one weighted code per structure in the sample of 200 has been included, with the most critical taken if there was more than one weighted code for performance of water management applied to a Benchmark Inspection report. The weighted codes were applied subjectively to extracts of text from the Benchmark Inspection reports, where the WSP inspector that witnessed the Benchmark Inspection recorded comments and observations that provide evidence to give judgement on performance of water management. The widths of the bars have been scaled to indicate the number of codes (taking only one per Benchmark Inspection report) applied to each category of age group. The categories are displayed in order of age group.

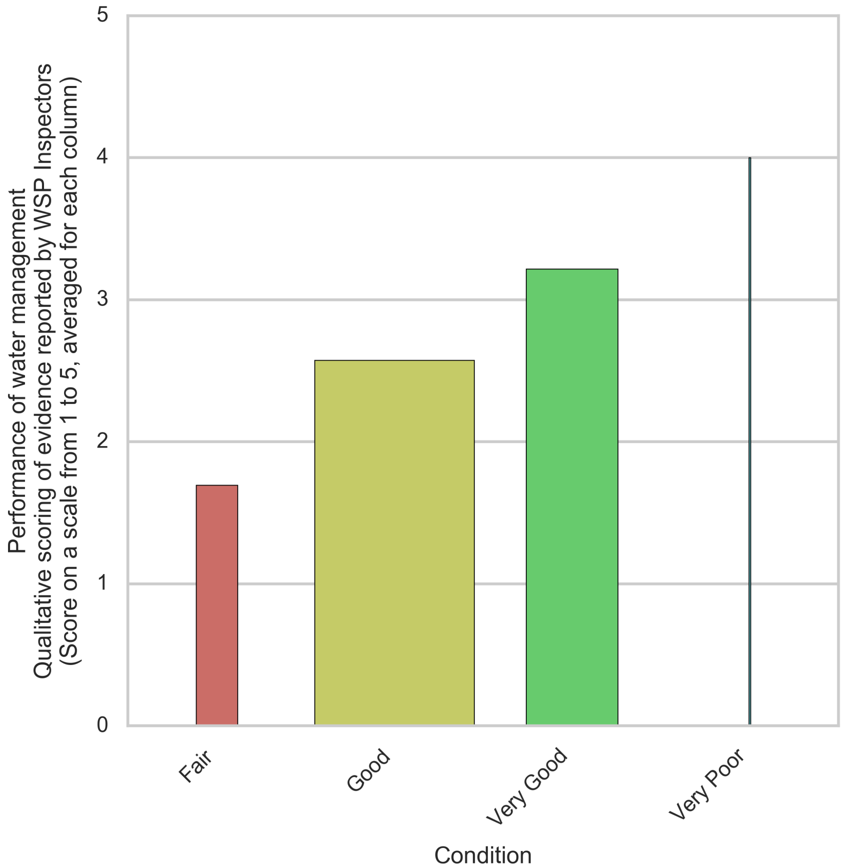

Figure 7.24: Performance of water management by condition.
This plot of qualitative weightings applied to codes in Dedoose.com, shows the average scores applied on a scale from 0-5 for performance of water management, split into categories of condition. Only one weighted code per structure in the sample of 200 has been included, with the most critical taken if there was more than one weighted code for performance of water management applied to a Benchmark Inspection report. The weighted codes were applied subjectively to extracts of text from the Benchmark Inspection reports, where the WSP inspector that witnessed the Benchmark Inspection recorded comments and observations that provide evidence to give judgement on performance of water management. The widths of the bars have been scaled to indicate the number of codes (taking only one per Benchmark Inspection report) applied to each category of condition. The categories are displayed in order of average applied weight.

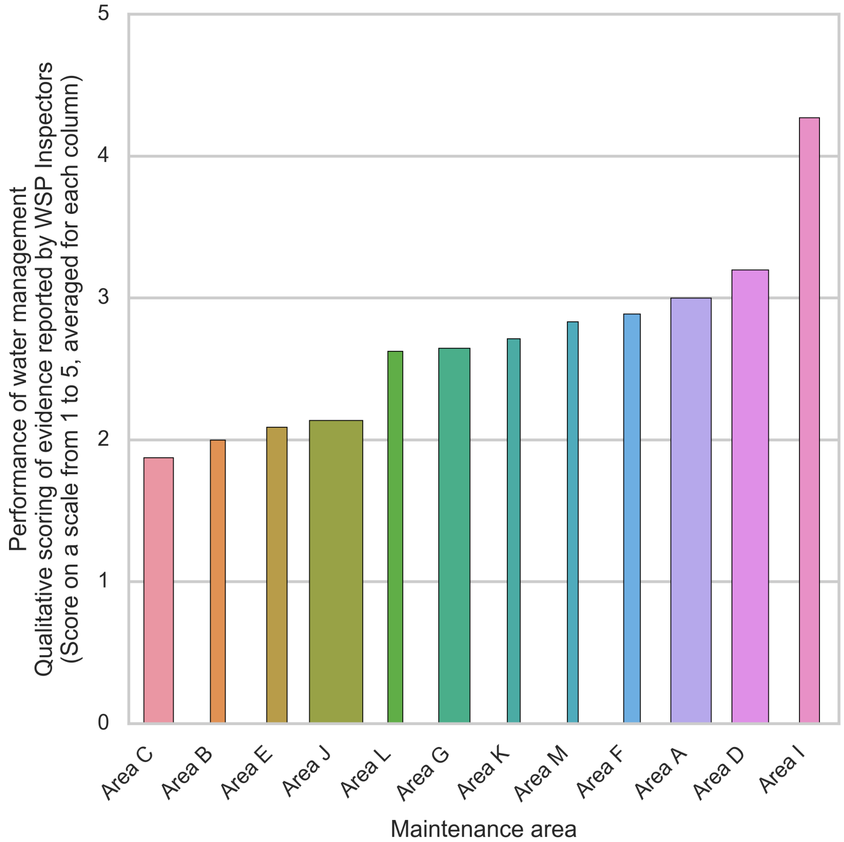

Figure 7.25: Performance of water management by maintenance area.
This plot of qualitative weightings applied to codes in Dedoose.com, shows the average scores applied on a scale from 0-5 for performance of water management, split into categories of maintenance area. Only one weighted code per structure in the sample of 200 has been included, with the most critical taken if there was more than one weighted code for performance of water management applied to a Benchmark Inspection report. The weighted codes were applied subjectively to extracts of text from the Benchmark Inspection reports, where the WSP inspector that witnessed the Benchmark Inspection recorded comments and observations that provide evidence to give judgement on performance of water management. The widths of the bars have been scaled to indicate the number of codes (taking only one per Benchmark Inspection report) applied to structures in each maintenance area. The areas are displayed in order of average applied weight.

7.4.5 Trends in the performance of repairs

WSP's inspectors were asked to record on the Benchmark Inspection Records whether there were any repairs on the structure and, if so, to comment on how the repairs appeared to be performing. These responses have been rated qualitatively on a scale from 0 for poor performance to 5 for excellent performance. Repairs were noted on 71 (35%) of the bridges in the benchmark inspection sample, with the average score applied to the performance of these repairs being 2.8.

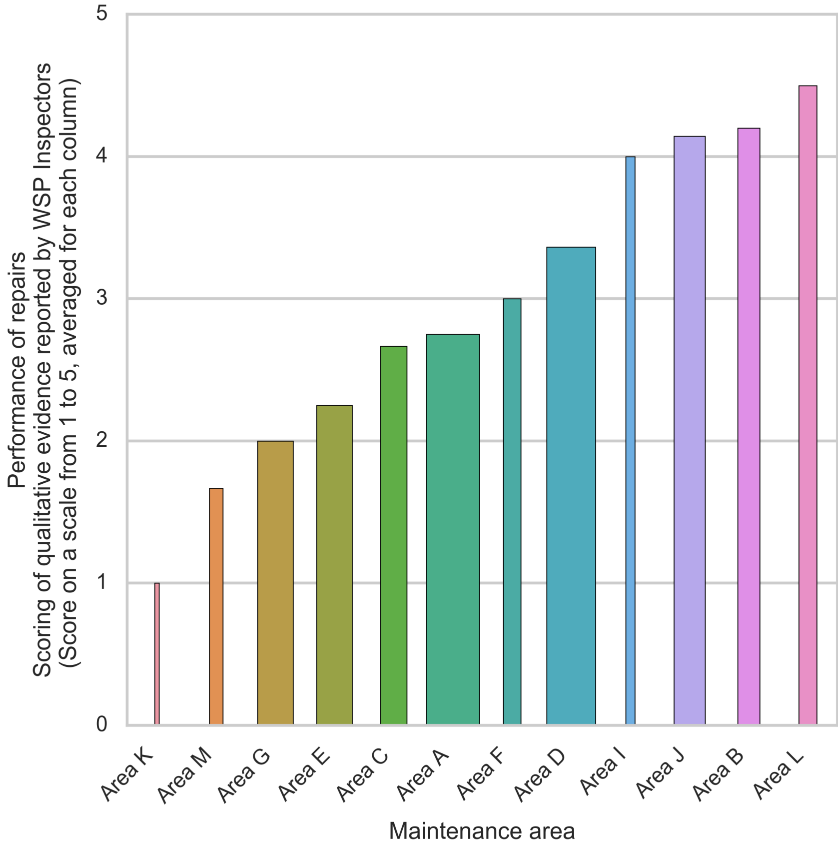

Figure 7.26: Performance of repairs by maintenance area.
This plot of qualitative weightings applied to codes in Dedoose.com, shows the average scores applied on a scale from 0-5 for performance of repairs, split into categories of maintenance area. Only one weighted code per structure in the sample of 200 has been included, with the most critical taken if there was more than one weighted code for performance of repairs applied to a Benchmark Inspection report. The weighted codes were applied subjectively to extracts of text from the Benchmark Inspection reports, where the WSP inspector that witnessed the Benchmark Inspection recorded comments and observations that provide evidence to give judgement on performance of repairs. The widths of the bars have been scaled to indicate the number of codes (taking only one per Benchmark Inspection report) applied structures in each maintenance area. The area are displayed in order of average applied weight.

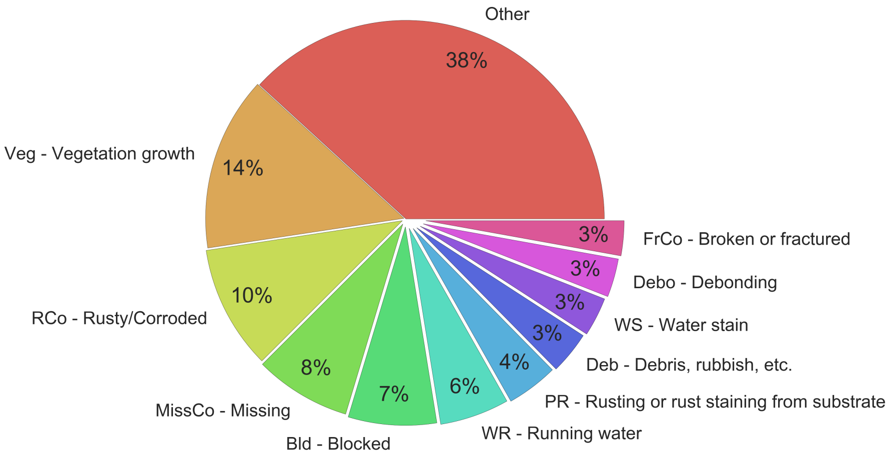

Figure 7.27: Recorded defect type for all defects in SMIS which are recorded to be caused by maintenance issues.
The ‘Other’ category includes all defect types for which there are fewer than 200 recorded defects.This plot has been produced from a download of raw defect data from SMIS obtained in February 2017 containing all currently valid defects. Where defects in SMIS have been applied to multiple components these have each been counted individually.

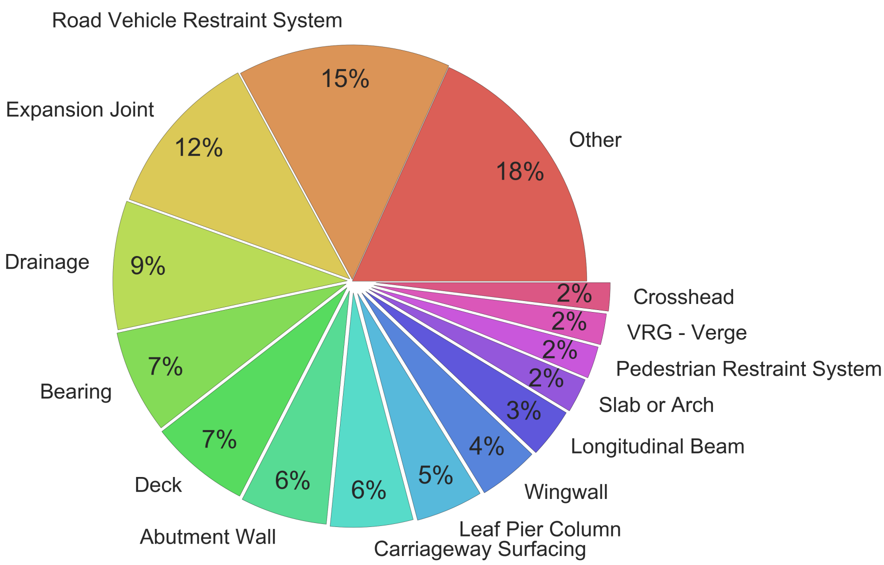

Figure 7.28: Recorded component type for all defects in SMIS which are recorded to be caused by maintenance issues.
The ’Other’ category includes all component types for which there are fewer than 200 recorded defects. This plot has been produced from a download of raw defect data from SMIS obtained in February 2017 containing all currently valid defects. Where defects in SMIS have been applied to multiple components these have each been counted individually.

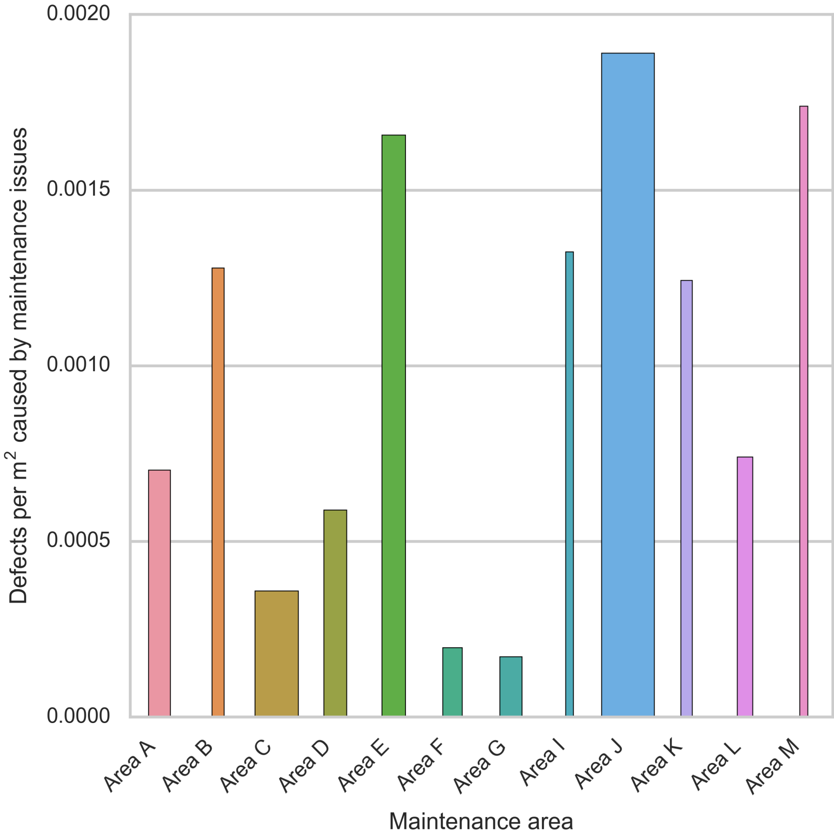

Figure 7.29: Variation in rate of maintenance defects per square metre of deck with maintenance area.
This plot shows the variation in the number of recorded maintenance defects with maintenance area. The average number of defects per square metre of deck is plotted for each *maintenance area*. The widths of the bars have been scaled by the total deck area of structures in each category, such that categories that represent only a small proportion of structures can be readily identified. This plot has been produced from a download of raw defect data from SMIS obtained in February 2017 containing all currently valid defects. Where defects in SMIS have been applied to multiple components these have each been counted individually.

7.5 Discussion

7.5.1 Factors affecting performance

The majority of Highways England's bridge stock was found to be in 'Good' or 'Very Good' condition when rated using the Average BCI score (BCI_{Ave}) (Table 7.2), with a slow rate of deterioration over the study period (Figure 7.4).

Figure 7.1 shows that, typically, elevated road structures are in the poorest condition. It can also be seen in Figure 7.8 that the rate of deterioration in average condition score (BCI_{Ave}) is fastest for elevated roads. However, the same trend does not appear to be repeated with the critical condition score (BCI_{Crit}). Instead, Figure 7.9 shows that the average rate of change of BCI_{Crit} for elevated roads is actually positive. This is very likely due to a relatively large number of maintenance interventions having been undertaken to rectify critical defects on elevated road structures during the study period. Large culverts are currently the structure type in the best condition, however they demonstrated some of the fastest rates of deterioration in both the BCI_{Ave} and BCI_{Crit} scores.

The current condition of overbridges can be seen to be better than that for underbridges. Additionally, underbridges can be seen to be deteriorating faster than overbridges. This appears to suggest that overbridges are generally more durable than underbridges. Considering that the decks of Highways England's underbridges carry the heavily gritted Strategic Road Network, it is possible that this poorer performance of underbridges is related to their higher exposure to chloride-based de-icing salts (carried by water leakage through defective deck waterproofing, drainage or joints), which is known to accelerate the deterioration of concrete structures (e.g. Vassie 1984; Wallbank 1989; Bamforth *et al.* 1997; Abosrra 2010). Given the well-established link between chlorides and the deterioration of common bridge components, further work should be done to establish whether the costs of the resulting deterioration are sufficient to justify transition to more expensive chloride-free de-icing products such as urea.

In Figure 7.2 it can be seen that continuous structural forms tended to be in better condition than structures which are simply supported. However, the calculated deterioration rates show that simply supported structures appeared to deteriorate slower than continuous structures. One of the findings of Wallbank (1989) was that deck expansion joints were often found to leak, leading to an increased likelihood of chloride contaminated water reaching bridge sub-structures, with a consequential increase in the risk of deterioration. Wallbank (1989) proposed that continuous structures should be adopted where possible to reduce this risk. However, the evidence presented here does not seem to suggest that continuous structures are significantly more durable than those which are non-continuous.

Figure 7.5 shows that the most important factor affecting the average condition score of a structure was its age, with older structures typically having lower condition scores than newer structures. Figures 7.6 and 7.7 identify a decrease in the rate of deterioration of condition scores with increasing structure age. This implies that, typically, the condition of structures initially deteriorates rapidly before gradually levelling off, providing a very different deterioration curve to that presented in standard reference texts (e.g. Ryall 2010, p.527), and those normally assumed for asset management purposes in the UK (Atkins, 2015). The results correspond well to studies undertaken using data for bridges in Illinois (Bolukbasi *et al.*, 2004) and Florida (Sobanjo, 2011), which show an initial higher rate of deterioration when structures are in a perfect condition, followed by a slower decline once structures are in a reasonable, but not excellent, condition. It is important to note, that this data includes the effects of both deterioration and maintenance interventions as it is not possible to remove the effects of maintenance from the condition data collected by inspectors. As a consequence of the inclusion of maintenance and renewals in this data, the lower end of the condition-time deterioration profile is likely to have been masked as interventions would have been made before structures' conditions fell to an unacceptable level (Highways Agency, 2014a).

After structure age, deck type and structure type were also found to be highly influential factors on the average condition score of a structure. Detailed insights can be drawn from the decision trees results, for example: the condition of simply supported highway overbridges and cantilever and suspended span structures in Area E, and simply supported elevated roads in Area J were found to be particularly poor, and were shown to be almost certain to be in below average condition.

The importance dendrogram plot in Figure 7.5 highlights that current condition and maintenance region were found to be the most influential factors affecting the rate of change of condition over time. Typically, structures reported to be in the best condition also had the highest deterioration rates, again implying that the condition of structures appears to deteriorate rapidly at first before levelling off later in their service life. This exactly opposite behaviour to the typical deterioration curves used to model bridges (such as the example shown in figure 2.1), where the rate of deterioration is assumed to increase as the condition decreases.

7.5.2 Performance of components

Primary structural components, longitudinal and transverse beams, were generally reported to be in worse condition than other components (Figure 7.3), and were also seen to exhibit some of the highest deterioration rates (Figure 7.10). Figure 7.3 shows that expansion joints were typically in poor condition and in Figure 7.10 that they also had a high rate of deterioration. This corroborates the finding of Wallbank (1989) that leaking expansion joints were frequently a cause for concern. From the results of this study, it appears that this is still the case. Drainage components were reported to be in fairly good condition, but with deterioration rates higher than most other components. Intermediate and end supports were reported to be in good condition, and improving over time, suggesting recent investment in maintenance to improve their condition.

7.5.3 Performance of repairs and maintenance

It is clear that there was more evidence of poor quality repairs than of good quality repairs. Most of the noted repairs were concrete repairs with many examples of cracking, spalling and honeycombing observed. It can also be seen, in Figure 7.26, that there were significant variations in the performance of repairs in different maintenance areas which could suggest that different maintenance approaches have been adopted. Any failed concrete repairs should be identified during a Principal Inspection and recorded in SMIS as a defect. Figure 7.27 shows the defect type for all defects in SMIS which are recorded to be caused by maintenance issues. It can be seen that the most commonly recorded form of defect related to maintenance was vegetation growth, followed by rusty or corroded components. Figure 7.28 illustrates the component types for all defects which are recorded to have been caused by maintenance issues. It can be seen that road vehicle restraint systems, expansion joints and drainage components had the highest number of recorded maintenance issues. It therefore appears that poor quality concrete repairs, which have been observed on site, are not being recorded in SMIS as defects caused by maintenance issues. Figure 7.29 illustrates that there were significant variations in the numbers of maintenance issues recorded in different maintenance areas. This could suggest that repairs are carried out more effectively in some areas than others, or that more repairs are required in some areas. Without information about the details of maintenance interventions undertaken, no firm conclusions can be drawn. Furthermore, since this data is as recorded in SMIS, there may also be differences in the way defect causes are recorded in each area. It would be beneficial for information about failed repair works to be consistently recorded in the Defect Cause field as this would allow bridge owners to more easily determine the life of typical repair works, and whether alternative techniques should be developed.

7.5.4 Performance of water management

Reviewing the Benchmark inspection data relating to the perceived adequacy of maintenance to water management, the following observations can be made:

- Adequacy of maintenance to water management appeared to be slightly better on newer structures than on older structures. This could either suggest that water management on newer structures is easier to maintain, or that water management on older structures has required more maintenance due to its age.
- Adequacy of maintenance to water management appeared to be better for steel bridges than for concrete or composite structures.
- Adequacy of maintenance to water management appeared to be better for footbridges and overbridges than for underbridges and subways. This could suggest that access for maintenance was easier for overbridges than for underbridges.

Figures 7.23 to 7.25 present data relating to the perceived performance of water management. The following observations can be made:

- Water management on newer structures did not appear to perform significantly better than on older structures.

- There appeared to be a strong correlation between the performance of water management and the overall condition of the structure (as indicated by the BCI_{Ave} score). This substantiates one of the conclusions from the Maunsell Report that water management is extremely important (Wallbank, 1989).

- Large differences were seen in the performance of water management on different deck types.

- There were noticeable differences in the recorded performance of water management between different maintenance areas. This could suggest that different areas implement differing maintenance regimes, or that there were favoured designs particular to each area.

7.5.5 Quality of construction

Data from defects where the cause was tagged as due to construction issues has been analysed to identify any trends. It is noted that some construction issues, especially on older bridges, may have been rectified in the past and will therefore not have been captured in this analysis. The plot in Figure 7.12 illustrates the variation in the number of recorded construction defects with structure age. The average number of defects per structure has been plotted for each structure age so that the large number of bridges built 40 to 50 years ago do not distort the results. It can be seen that the average number of construction defects was lowest for structures aged between approximately 15 and 30 years, and was noticeably higher for both older and younger structures. The overall rate of construction defects has increased steadily over the 25 year period from 1991 to 2016, this appears to correlate with the increased use of Design and Build contracts and of self-certification of construction quality following the introduction of the NEC contract suite in 1993 (ICE, 1993). The plots in Figure 7.13 and 7.14 show that there were a large number of different defect types on different components which have been attributed to construction issues. The most common construction issues appear to relate to missing parts of road vehicle restraint systems and rusty nails or tie wire in slabs and arches. In Figure 7.15 it appears that there was a higher rate of construction defects on overbridges than on underbridges. There were also noticeable differences in the average number of construction defects per bridge recorded in each maintenance area (see Figure 7.16). This may represent differences in the quality of construction between areas, but could also suggest that some areas have corrected more construction related defects than others, or that the reporting of defects differs between areas. In Figure 7.17 it can be seen that continuous bridges appeared to exhibit a noticeably lower rate of construction defects than most other structural forms.

Reviewing the changes in the prevalence of individual types of construction defect, exposed reinforcement was much more prevalent in older structures than newer structures. It is possible that this could relate either to the amount of time that it takes for sufficient corrosion and spalling to occur such that reinforcement is exposed, or improvements in construction quality such that sufficient levels of cover are consistently achieved on site.

It can be seen in Figure 7.20 that significantly more evidence of poor quality of construction was observed during the Benchmark Inspections on concrete and composite bridges than on steel bridges. This aligns with the finding from the SMIS data that there were a larger number of construction defects per structure on concrete and composite bridges than on steel structures. Figure 7.21 illustrates a significant variation in the amount of evidence of poor quality of construction found in different maintenance areas. It can be seen in Figure 7.16 that there was also a significant variation in the average number of construction defects per structure in each area. There is, however, very little correlation between these two plots. For example, WSP's inspectors observed the least evidence of poor quality construction in Area 13, whereas Area 13 had almost the highest average rate of construction defects per structure. A similar observation can be made about structure types. In Figure 7.22 it can be seen that more evidence of poor quality construction was observed on underbridges than on overbridges. However, in Figure 7.15 it can be seen that a larger number of construction defects have been recorded on overbridges than on underbridges. These findings could suggest that it is difficult to reliably identify the cause of some problems with structures, or that there are a large number of less severe defects relating to construction issues which were observed by WSP's inspectors but were not severe enough to have the defect cause recorded in SMIS. Alternatively, it could suggest that evidence of poor quality construction does not necessarily mean that there are defects.

7.5.6 Availability of data and opportunities for the future

The data made available for this work comprised a large dataset including detailed inventory information for all the bridges on England's motorway and trunk road network, and the individual components of which they comprise. The hierarchical component inventory was enhanced in 2007 to include a greater level of detail, for example including 'child' components such as 'prestressed concrete beams' under 'parent' components such as 'deck'. Recording of condition information from Principal Inspections was migrated to this new detail level on a bridge by bridge basis between 2007 and 2016. As condition scores calculated from defect data recorded at this higher level of detail are not comparable with those used previously, tracking and analysis of individual bridges' conditions over time was only possible from 2007 onwards, and then only for a sub-set of the stock. The corollary of this is that 2016 marked the first practical point in time that this study could be undertaken, and that for rate of change in condition, this work was necessarily limited to comparing changes over only one full Principal Inspection cycle (including two intermediate General Inspections) and for only a sub-set of the full stock of bridges.

Identifying trends in the condition of the stock was complicated by the lagging effect the 2yr/6yr General/Principal Inspection cycle has on recording of changes in condition. Further, as the rate of deterioration for many components is slow, and the defect grading system is coarse, some components may stay recorded at the same condition for several inspection cycles. Without the full time-history of condition for all the bridges on the network, it is difficult to determine how long an individual component has been at a given condition rating, and therefore its rate of change if it has changed. Additional complexity is added by the variability between the opinions of inspectors from one inspection to the next. For rapidly deteriorating, or short lifetime elements, there is a risk that the inspection interval is too infrequent to reliably detect defects before components enter a dangerous state (Sheils *et al.*, 2012). A relatively simple amendment to the specification for the data recorded to include categorisation of the rate of change since the previous inspection could assist in resolving these issues (see Chapter 8).

This chapter focuses on insights from condition data as recorded during visual inspections and notes that the relationship between condition, and key performance characteristics such as capacity, safety and serviceability is complex.

With all bridges now migrated to the more detailed recording format, and an ever-increasing number with more than one Principal Inspection recorded in this new format, there is potential for analysis of this data to be used to inform decision making. The historic condition data could be used to calibrate and update deterioration models and could begin to fulfil the aspirations of an integrated Bridge Management System where data on past performance is used to influence decision-making for interventions (e.g Woodward *et al.* 2001 - the BRIME project) which, while reported to be in other countries (e.g. Shepard 2005 (USA), Mirzaei *et al.* 2012 (Global)), are not widely adopted in the UK (Bennetts *et al.*, 2016).

Asset condition data as used in this study requires in-depth visual inspections to obtain, which can be costly and require disruption to the highway network, it is therefore important that the value of the data is recognised by bridge owning organisations and that it is stored and managed accordingly. Furthermore, as the value of the data increases the longer the dataset available, it is crucial to avoid changes to the way in which data is collected that are not backwards compatible to ensure that data collected today can still be used.

7.6 Concluding remarks

- A range of data analysis and presentation techniques have been demonstrated which can provide significant additional insight into existing data held about the current condition (and rate of change of condition) of Highways England's bridge stock.

- Optimal decision trees have been used to identify the most influential factors in the performance of structures and present these multi-factor trends in a format readily digested by decision makers.

- Age, deck type, and structure type were found to be the most influential factors affecting the average condition score (BCI_{Ave}) of bridges on Highways England's network.

- Further work should be done to establish whether the costs of the chloride induced deterioration are sufficient to justify a transition to more expensive chloride-free de-icing products.

- Structure Condition was found to be the most influential factor in the rate of deterioration, with structures in a better condition found to be deteriorating at a faster rate than those in a worse condition.
- Newer structures were also found to be deteriorating at a faster rate than older structures, suggesting that the condition of structures initially deteriorates rapidly before gradually levelling off. This is contrary to commonly assumed deterioration profiles in textbooks (Ryall, 2010) and implemented in asset management systems (e.g. LoBEG 2009, Atkins 2015).

Chapter 8

Suitability of Visual Inspection Data for Decision Making

The work presented in this chapter will be reported in Bennetts et al. *(2020).*

Bennetts J., Webb G. T., Denton S. R., Nepomuceno D. & Vardanega P. J. (2020) Looking to the future of bridge inspection and management in the UK. In: *Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges: Proceedings of the Tenth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2020), Sapporo, Australia. In Preparation.*

8.1 Introduction

The preceding chapters of this thesis have demonstrated that current bridge management practice relies upon visual inspection data to make decisions about the type and timing of interventions to maintain or improve bridge structures (chapter 4). However, chapter 6 demonstrates that the subjectivity of the inspection process results in significant uncertainty in the data recorded at visual inspections. The consequence of this is that seemingly-sensible strategies for prioritising work (such as ranking by critical condition score) are not robust, because they are highly sensitive to uncertainties in the underlying data. It has also been shown that structural investigation techniques, such as carbonation or chloride ion testing of concrete structures, do not provide a solution to improving the reliability of the visual inspection condition scores (section 6.4). Chapter 7 demonstrates that, notwithstanding the low reliability of individual defect scores, there is significant value in the visual inspection and inventory data-sets held by bridge owners and that there is great opportunity for modern data-processing techniques to identify trends in performance at a stock or sub-population level. Chapter 9 outlines the importance of the rate of deterioration in controlling whether it is financially prudent to intervene quickly or delay an intervention for as long as possible. It also shows that if it is sensible to delay for as long as possible, then predicting the final point at which the current intervention is possible becomes the crux of intervention planning.

The literature (chapter 2) can present a picture of seamless integration between 'smart' sensors and numerical recipes to predict asset need and design optimum intervention strategies. The reality is that, in the vast majority of cases, UK bridge managers identify maintenance needs through visual inspections and decide where to spend stretched budgets on a reactive basis. The processes used to make these decisions are immature, and there is evidence that clumsy attempts to formalise and automate them have resulted in contention between the processes and the judgement of the experienced asset stewards that implement them (chapters 4 and 5). Taking the perspective of stakeholders and considering the holistic requirements for bridge condition data, this chapter sets out the key user-groups for bridge condition data, and reflects on the suitability of the current data collection practices to meet the needs of these users. In particular, it identifies the critical importance of rate of change in condition for users of the data and highlights the significant intrinsic deficiencies in the ability of the current severity-extent recording format to reliably measure it.

8.2 Usage of condition data within bridge management organisations

The use of condition data within asset management organisations can be split between tactical/operational considerations regarding the management of individual assets, and strategic considerations about portfolios of structures. While there are commonalities between these two primary users - they are both interested in the current and future condition of structures - there are also significant differences. The operational teams need to be able to identify what work is required on their structures and have sufficient detail about the nature of defects to plan remedial action and prepare a bid for funding/prioritisation. The central, strategic, teams need to understand the likely on-going maintenance costs to plan medium and long-term budgets. What is particularly important for both user-groups is an understanding of not only the condition of each asset, but also the rate of change of condition of with time.

8.2.1 Strategy and planning

Understanding the rate of change of asset condition is a fundamental capability for a modern asset management organisation, particularly as it directly controls the cost of the future maintenance burden. At a portfolio level, information regarding the changes in condition of a stock of assets is required to inform strategic, organisational decisions regarding the policies and funding required to maintain an infrastructure network in a safe and serviceable state. Information about changes in condition is also used to identify trends in the performance of different types of asset (chapter 7, UK Roads Liaison Group 2016, Bennetts *et al.* (2018b)), inform the development of standards and policies for design and maintenance (e.g. Wallbank (1989)), and develop programmes of work. The current condition state is often used as a proxy for the level of asset risk carried by an organisation, and can be reported to a regulator to demonstrate that due diligence is being observed in the stewardship of a network's asset base. Current condition data can be combined with deterioration modelling techniques to predict the future condition performance of a stock of structures under different scenarios of maintenance intervention funding and strategy. Typically, it is common for the results of 'planned preventative', 'reactive' and 'do minimum' intervention scenarios to be forecast, with differing levels of funding constraint. The simulations are typically run with either a cost or condition target applied. Such forecasts typically use stochastic modelling techniques, iterating a solution over yearly time steps. The assumed rates of deterioration are a key variable in these models, and it is vital to have both accurate records of past rates of change to calibrate models, and to understand the current rate of change of assets to predict their future performance.

8.2.2 Management of individual structures

The importance of understanding the rate of change in the condition of a structure or element is well understood by bridge managers because a defect that is stable and has been present for a long time is usually significantly less concerning than one which has appeared recently and is getting worse quickly. The rate at which a defect is getting worse will have an impact on the timing and urgency of a repair. Management of structures must also consider the deterioration of critical elements that are hidden, and Collins *et al.* (2018, p10) suggest that, amongst other measures, "...regular routine examination(s) of the hidden element: revisit to assess change in condition" may have averted the collapse of Stewarton Bridge (RAIB, 2010). There may be a whole life cost advantage in proactively planning to undertake preventative maintenance operations at an optimal time - avoiding deterioration causing a shift in the nature, scale and cost of interventions (e.g., Woodward *et al.* 2001, Yanev & Richards 2013). Elements in a rapid rate of decline are at risk of falling into a state where costly and disruptive urgent reactive maintenance is required. In an ideal scenario, accurate measurement of current condition and its rate of change would allow identification of the optimum point for intervention, avoiding this risk and enabling a shift to a better value planned preventative maintenance regime.

8.3 Limitations of current data recording for understanding rate of change

The condition data recorded for the UK's bridges is valuable in managing structures and is a crucial component of decision making processes (Chapters 4, 5). However, there are aspects of the form and content of the data that limit its utility both for managing individual structures and informing strategy. In particular, the utility of the data collected suffers from the granularity of the severity and extent scoring, and the subjectivity of inspectors, which make it very difficult to reliably assess the rate of change of condition.

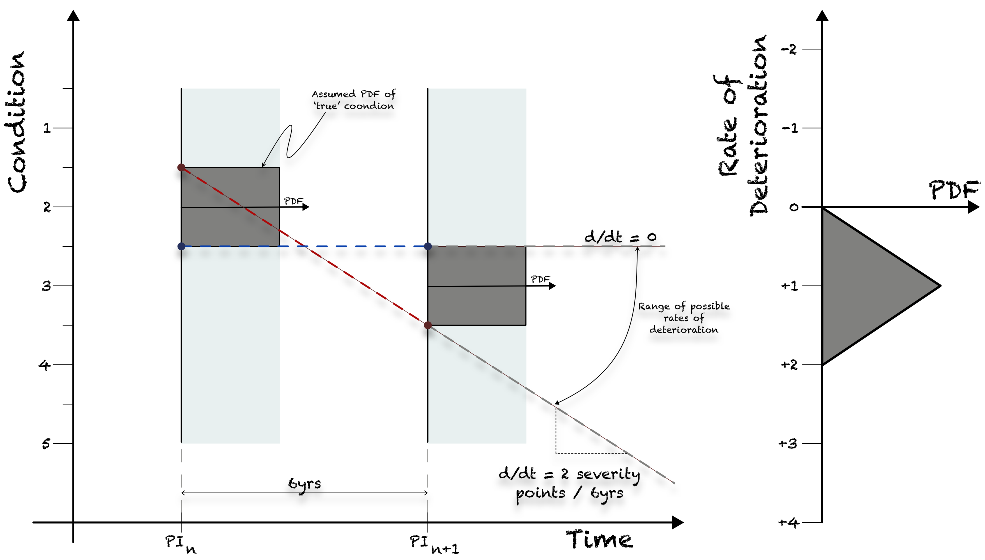

Figure 8.1: Sketch showing the uncertainty in inferring rate of change from a change in defect score.

8.3.1 Implications of the lifetime of bridge elements

The long lifetime of bridge components results in many structural elements remaining at the same recorded condition grade for decades. For example, a reinforced concrete component with a severity score of 3 would be expected to remain with a severity of 3 for between 10 and 60 years, depending on exposure (Atkins, 2015). One cannot know how long an element has remained at a given condition, unless it has changed condition since the current data recording regime commenced in the early 2000s (Sterritt & Shetty (2002)). Transitions from one condition band to the next are infrequent and yet provide the only method by which the rate of deterioration can be estimated from current data. However, as discussed in the next section, the granularity of the recorded condition data also means that a transition from one condition band to another does not provide much evidence as to the underlying rate of deterioration.

8.3.2 Uncertainty in determining rate of change from visual inspection data

Figure 8.1 illustrates the uncertainty in assessing the rate of deterioration from a reported transition of condition from a severity score of 2 to a severity score of 3 between two Principal Inspections. Noting that a reported score of 2 could be applied to a defect which is only just worse than a 1 up to a defect that is only just better than a 3, it has been assumed that the Probability Density Function (PDF) representing the 'true' severity is constant over the range from 1.5 to 2.5. Applying a similar distribution to the reported condition of 3 at the following Principal Inspection (PI), the PDFs for the 'true' condition have been plotted on Figure 1 as rectangular blocks. Figure 1 demonstrates that the rate of change of condition implied from this reported transition from a severity score of 2 to 3 lies

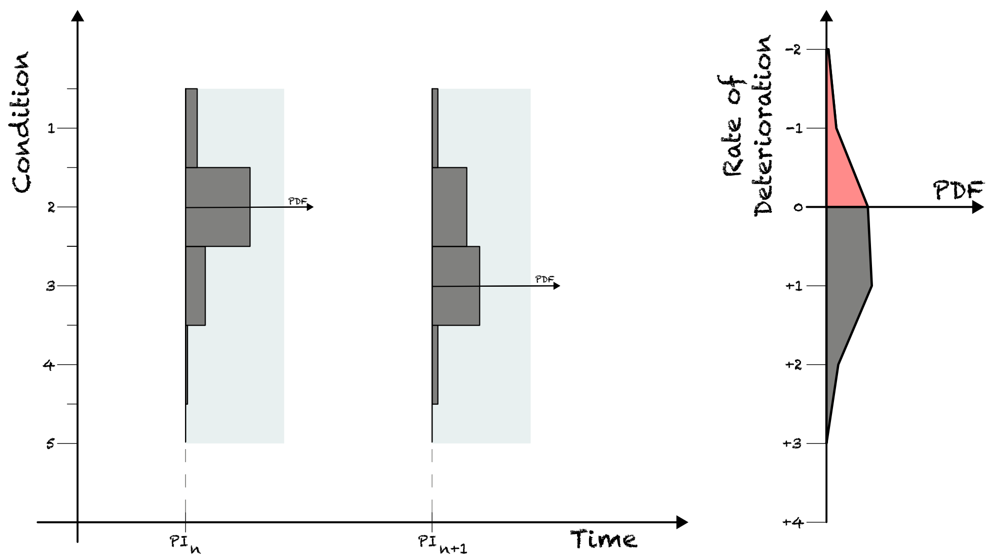

Figure 8.2: Sketch showing the uncertainty in inferring rate of change from a change in defect score - including the effects on uncertainty in defect scoring

between zero change (blue dashed line), and an on-going rate of change of two severity points over the 6yr PI period (red dashed line). Returning to the above discussion of planning for preventative maintenance interventions - a rate of change of 2 severity points over 6yrs would mean urgent action would be required to prevent failure of the element before the next PI, a rate of change of 1 PI point over the 6 years would likely mean that preventative maintenance would be required before the next PI, whereas a rate of change of zero could imply that no interventions will be required for some time.

The ability to use reported changes in the condition of an element to imply rate of change of condition is further hindered by the uncertainties arising from variations in defect scoring between different inspectors. Chapter 6 presents the results of a study into the reliability of defect scoring by inspectors on Highways England's network. The study comprised double inspection of 988 defects across a representative sample of 200 bridges on the network (chapter 6, Bennetts *et al.* 2018a). The defect severity and extent scores applied by WSP's bridge inspectors and Highway England's service providers were compared and used to derive empirical probabilities, characterising the uncertainty in visual inspection data (chapter 6). The empirical probabilities for uncertainty in reported condition (given in chapter 6 and Bennetts *et al.* 2018a) have been used in this chapter to demonstrate the effect of uncertainty in visual inspection data on the uncertainty in the implied rate of change. Figure 8.2 shows the probability density functions for the reported severities of 2 and 3 from chapter 6 as a series of uniform steps, with the total area summing to one. Figure 8.2 also shows the resulting PDF for the rate of change of condition (in units of severity score per 6 years). The uncertainty in the severity assignment results in a much broader range of possible 'true' deterioration rates. It is possible, albeit vanishingly unlikely, for the 'true' deterioration rate to be as high as 4 severity points per 6 years, or as low as negative (i.e. improving by) 3 severity points every 6 years. Importantly, the ‘true’ condition of elements should not be able to improve over time without maintenance interventions (which ought to remove the relevant defect). However, the prediction of such anomalies is supported by examination of the data held within Highways England’s SMIS database (Bennetts *et al.*, 2017), which shows that the reported condition of elements is almost as likely to improve between inspections as it is to decline. These spurious changes (which could be due to uncertainties in defect scoring or errors in reporting) have significant implications if the data are to be used to calibrate algorithms for prediction of future performance, or by bridge managers to inform decisions.

8.3.3 Discussion

Understanding the current rate of deterioration is fundamental for both the planning of maintenance on individual structures, and for bridge managers’ strategic planning at a portfolio level. However, the present system of recording only the current state of assets is ineffective at measuring the rate of deterioration. Even assuming perfect inspection reporting, rates of deterioration calculated from changes in reported condition do not give sufficiently accurate data to differentiate between elements that require urgent repairs, and those require no repairs. The reliability is further reduced by known variabilities in recording of condition by inspectors, and the surprising predictions that some elements might be reported to get better are borne out in real-world data.

The current programme of bridge inspection has remained unchanged for several decades and costs millions of pounds per year. It also requires a disruptive rolling-programme of road and rail closures. Given the scale of the inspection programme and national importance of the infrastructure it safeguards, it is vital that the value of the data collected is tested against the effort and expense of collecting it. With the current system of collecting and recording condition data it is not clear that this test is met - the current data is unreliable and fails to provide some of the most important parameters for the management of infrastructure.

A paradigm shift is required to transform visual inspection practise and place a much greater emphasis on understanding and recording change, rather than the current approach of recording only the current state at regular time intervals. Recording an assessment of the rate of change of defect condition would address many of the deficiencies of inferring rate of deterioration from the condition data alone and would filter out spurious improvements (or deteriorations) and enable identification of elements that are genuinely changing rapidly. Recording change would also reduce the uncertainty in the current condition, as comparison against previous recorded conditions would rule-out some of the possible ‘true’ condition values. Recent advances in technology (e.g. Structural Health Monitoring, computer vision and machine learning) provide the opportunity to review the approach to bridge condition monitoring and may enable systems and processes to derive better information from visual inspections and augment the visual inspection regime.

8.3.4 Practical proposals for the recording of rate of change

Recording the 'true' rate of deterioration in severity points per year would not be practically possible during inspections, and any attempt to ask inspectors to estimate a rate of change quantitatively would be prone to significant measurement error. However, noting that condition is recorded as individual defects on the elements of a structure, the degree of change could be classified as showing:

- Little or no change in the defect since the last inspection, or
- the defect shows some deterioration since the last inspection, or
- the defect shows significant deterioration since the last inspection.

Recording a simple qualitative assessment of the rate of change of defects' criticality in this way would address many of the deficiencies of inferring rate of deterioration from the condition data alone and could facilitate identification of elements that are genuinely changing rapidly. Anomalies such as spurious improvements in the inferred rate of change of condition could be addressed in inspection reporting software by simply asking inspectors to review the notes and photographs from previous inspections and comment upon any changes in reported condition. Simple disagreements in defect classification between inspectors could be filtered out by asking inspectors to record that they do not agree with the score given by the previous inspector, or note that unrecorded maintenance interventions appear to have been undertaken. Knowledge of a defect's scoring from a previous PI, combined with a qualitative assessment of its rate of change would also reduce the uncertainty associated with the current condition, by eliminating some of the possible values in the PDF for the 'true' condition. It is envisaged that this recording process could be incorporated into the Bridge Management System (BMS) software packages that are used to, inter alia, record condition data from visual inspections. The software could automatically present the relevant information from the previous inspections and in doing so promote reflection of previous inspection reports by inspectors.

8.3.5 Separating inspection capture from recording - a platform for innovation

The current processes and standards for the visual inspection of bridges in the UK require 'Inspectors' to visit bridge sites to inspect the structure, take photographs and make notes. In most cases the defects are recorded digitally at a later date, once back in the office, although the use of tablet computers to record inspection data in the field is increasing. This current reality of a labour intensive manual process is very different from a future vision where automated data capture systems (e.g. drones, vehicle mounted cameras etc) detect defects and a machine-learning system predicts future deterioration and plans the optimum interventions. Making the transition from the current reality to future aspiration is unlikely to be possible in one step. However, restructuring the way we undertake bridge inspections to explicitly separate out the fundamental stages would allow the more achievable goal of bringing innovation to each stage in turn. These stages are: image capture, identification of defects, grading of defects, interpretation of change over time, and decisions regarding maintenance.

With the exception of separating the image capture from the interpretation of those images, current bridge management systems are already set up to operate in this way for the current manual process for each of the tasks. If it can be shown that separating the image capture from interpretation does not have an overly detrimental effect on the reliability of the data, then this framework could open the opportunity to seamlessly apply innovations as they develop in fields such as image processing, drones, computer vision and machine learning.

8.4 Concluding remarks

This chapter has shown that the need for accurate information regarding the rate of change of condition is as important to the management of assets as information regarding the current condition. The rate of change of condition is crucial in the effective planning of maintenance interventions and in forming strategic operations. However, the current industry practice of recording the present condition of defects on structures at defined intervals does not provide sufficiently accurate information regarding the rate of change in condition. The variability of defect recording by inspectors adds additional uncertainty, and further reduces the fidelity of implied rates of deterioration. Recording an assessment of the rate of change would improve the ability of bridge managers to identify components or structures which are likely to be deteriorating rapidly, and help to reduce the magnitude of uncertainty surrounding the process of assessing current condition and relating this to deterioration models. The huge potential for technology to augment and improve upon current visual inspection practice could be unlocked by separating the tasks of image collection, interpretation and decision making.

Chapter 9

The Response of Bridge Stocks to Decision Making Strategies

This chapter is partly based on work presented in Stacy & Bennetts (2014).

Stacy M. B. & Bennetts J. (2014) *Structures VMR4 Value Management Review. Technical report,* WSP | Parsons Brinckerhoff, on behalf of Highways Agency

9.1 Introduction

Bridge owners must plan and deliver maintenance interventions to ensure their assets remain in a safe and serviceable condition, while keeping expenditure within the budget available. Government bodies are required to justify that expenditure represents 'value for money' for the taxpayer (HM Treasury, 2018). Typically value for money is demonstrated by showing that the benefits of a given expenditure outweigh the costs, using a Benefit Cost Ratio (See 2.6). Whilst many studies have shown preventative maintenance programmes and a whole life cost approach to offer better value for money and lower risk over the long-term, practitioners report that the majority of schemes are still reactive in nature. The work presented in Appendix A demonstrates, through a series of case studies on Highways England's network, that as an asset's condition deteriorates, changes in the viability of different intervention options can cause step increases in the cost of maintenance. In this chapter, the implications of these transitions and financial discounting on individual asset decisions are considered and some simple rules are observed for the 'optimum' timing of interventions.

An idealised stochastic model of a bridge stock is presented, which shows that a focus on annual cost and uncertainty in the timing of transitions between intervention options can cause organisations to lose control of the cost of maintenance and fail to deliver value for money. An abstract model of condition, deterioration, time and cost of intervention for a single asset, based on the observations in the case studies (Appendix A), has been used to build a stock-level model of behaviour. The model has been based on the deterioration of an element or elements and the scheme or schemes required to address this deterioration. Depending on the case study being considered and the nature of the intervention scheme, the model may be considered to act at element level, on groups of elements or at structure level. The model has been designed to investigate the global behaviours, i.e. trend in asset performance and expenditure, caused by an asset-level decision model. Simulations have been run for several scenarios to identify characteristics of the stock response to different funding conditions.

9.2 The consequence of a discontinuous cost-condition relationship on decisions

9.2.1 Benefit Cost Ratios

In Section 2.6, it was shown that the when applied to maintenance interventions, the commonly-used Benefit Cost Ratio approach can be expressed as:

$$BCR = \frac{WLC_{DoMin}}{\text{Current cost of the scheme}} - 1 \tag{9.1}$$

Reviewing this equation and noting that, under the assumption that there is a linear relationship between condition and cost (See 2.3.2), the 'do minimum' option is simply a deferral of the proposed scheme by N_{delay} years, Equation 9.1 becomes:

$$BCR = \frac{\text{Scheme cost} \times \text{increase due to deterioration} \times \text{Discount for } N_{delay} \text{ years}}{\text{Scheme cost}} - 1 \tag{9.2}$$

Where:

$$\text{increase cost due to deterioration} = (1 + R_{cost})^{N_{delay}} \tag{9.3}$$

$$\text{discount for } N_{delay} \text{ years} = \frac{1}{(1+\alpha)^{N_{delay}}} \tag{9.4}$$

And:

R_{cost} is the annual rate of growth in scheme cost due to deterioration, which is a constant if the rate of deterioration is constant and the cost of intervention is inversely proportional to the condition.

α is the discount rate, which in most UK examples is the Treasury Green Book value of 0.035, or 3.5%.

Substituting into Equation 9.2, gives:

$$BCR = \left(\frac{1 + R_{cost}}{1+\alpha}\right)^{N_{delay}} - 1 \tag{9.5}$$

Under this formulation of BCR, whether the benefit of a scheme is assessed as outweighing the

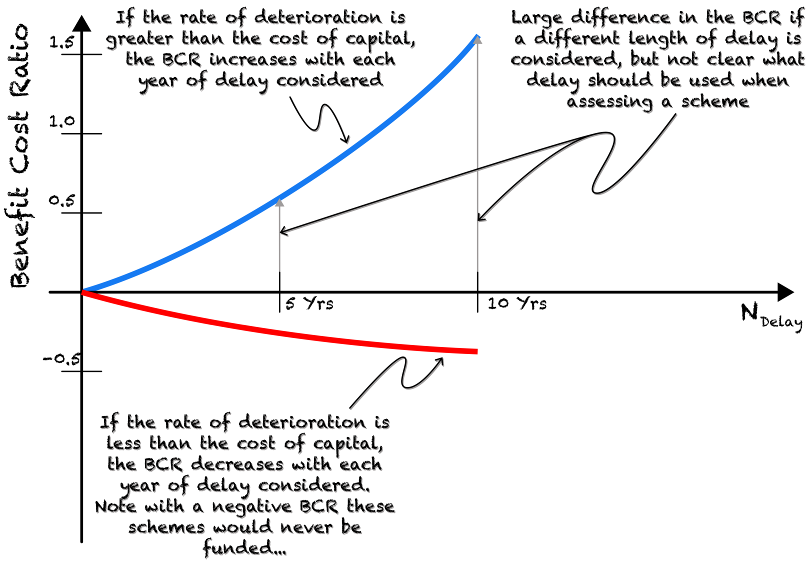

Figure 9.1: Sketch showing the variation in Benefit Cost Ratios with scheme delay. (Indicative values are approximately for a case where the annual change in costs is either 13.5% (blue line) or 0 (red line), and the discount rate is 3.5%)

cost (and may therefore be funded) depends solely on whether the additional cost each year due to deterioration in condition (as a percentage of the scheme cost) is greater than the discount rate applied in calculating the WLC of the deferred scheme (Figure 9.1). If the predicted rate of increase in scheme cost per year is greater than the Treasury discount rate, then the BCR will be positive and will increase with the considered delay period. However, if the predicted rate of increase in scheme cost per year is lower than the discount rate, then the BCR will be negative, and will decrease with increasing delay period - these schemes would not be funded.

Figure 9.1 shows that the BCR can vary considerably with the delay assumed, $N_{delay}1$, between the 'do something' case and a 'do minimum' which consists of the same scheme in a future year. However, it is not clear what value of $N_{delay}1$ ought to be used if the delay is perpetually deferred. With annual budgets, the decision can often become a choice between doing a scheme this year or next year, (i.e. $N_{delay} = 1$). The result of this is that even where the rate of cost increase due to deterioration is greater than the discount rate, the resultant BCR is low, and schemes are unlikely to justify investment each year, creating a situation where schemes are perpetually deferred from one year to the next.

The flawed-logic of this perpetual deferment can be seen by considering an example where there is a 10% difference between the deterioration rate and discount rate (blue line in Figure 9.1). In this case the BCR can be calculated for delay periods of 1 year (BCR = 0.097) and for 10 years (BCR = 1.52). If a scheme is deferred annually for 10 years then the BCR generated each year fails to reflect the actual BCR for the 10-year deferral, which should be an order of magnitude greater.

Further, in practice, many components will follow a stepped profile of intervention options with condition, and a comparison of the cost of a preventative scheme vs a 'do minimum' option of doing the same scheme next year will fail to quantify the benefit of avoiding a much more costly reactive or emergency scheme.

9.2.2 The effect of steps between viable intervention options

At first reading it might seem reasonable to conclude from Section 9.2.1 that intervention planning can be dealt with as two cases:

Case a Proposed interventions where the annual growth of intervention cost is lower than the cost of capital have a negative BCR and should not be funded (red line on Figure 9.1).

Case b Proposed interventions where the annual growth of intervention cost is greater than the cost of capital have a positive BCR and should be funded (blue line on Figure 9.1). The question then becomes what value of delay should be used to calculate a BCR to compare and prioritise against other potential schemes.

However, this assumes that the proposed interventions will always be an option. If instead the intervention being considered is only viable up until the condition of the structure or component reaches a certain state, after which point the only available options are more costly, the conclusions would be different. The *case a* schemes are likely to become viable if the costs the far side of the transition are considered. For the *case b* schemes, the same question remains but is even harder to answer - what delay should be considered in calculating the BCR scores?

It is not clear which future year or intervention option *should* be used for a cost benefit analysis in year 0. Choosing to compare against an emergency intervention in year 10 might capture the benefit of avoiding a reactive intervention, but is unlikely to represent the 'expected' outcome for all structures; meanwhile, at the other end of the spectrum comparing a scheme in year 0 against doing the same scheme in year 1 undervalues the benefits of doing the scheme today. The American bridge management system, Pontis, attempts to address this by calculating the cost and likelihood of all potential future states (Thompson *et al.*, 1998), however, such an approach relies on the availability of sufficient data to define each of the parameters, and would not capture previously unseen, or very low-frequency risks. Instead, the decision-making process could be flipped such that, rather than repeatedly asking *"should we do this work now, or next year?"*, instead the question should be *"when is the best time to do this work?"*

The answer to the question *"when is the best time to do this work?"* lies in considering the net present costs around the transition point between the cheapest proposed intervention (**Option 1**) and the cheapest alternative option once Option 1 is no-longer viable (**Option 2**). Figures 9.2 and 9.3 demonstrate the characteristics of these transition periods for cases where the net present cost decreases (*case a*) and increases (*case b*) with delay respectively. Within the time-frame of funding and inspection cycles, the timing of the transition is assumed to be unknown, or effectively unknowable.

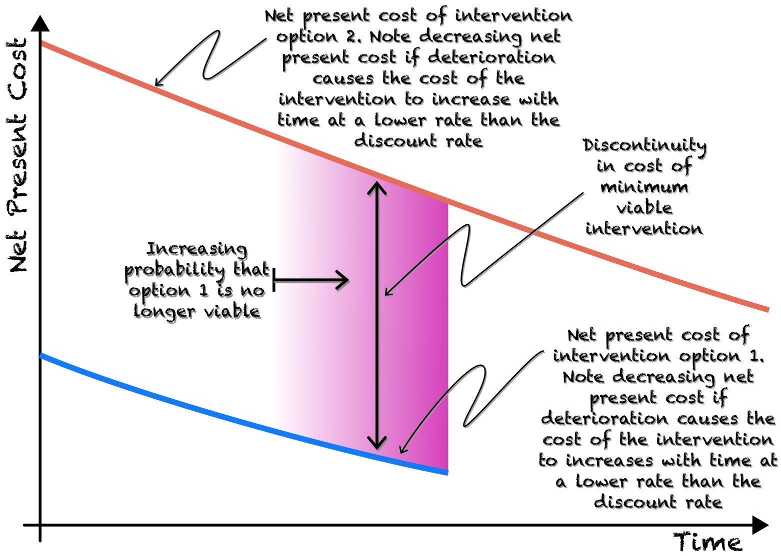

Figure 9.2: Sketch showing the general behaviour of Net Present Cost (at year zero) with time of intervention, for **case a** where the increase in cost of the scheme under consideration per year due to on-going deterioration is lower than the cost of capital (discount rate). Note that in this case, delaying the intervention in the short term has potential to save money. However, the longer the delay, the higher the risk that a lower cost intervention is no-longer viable.

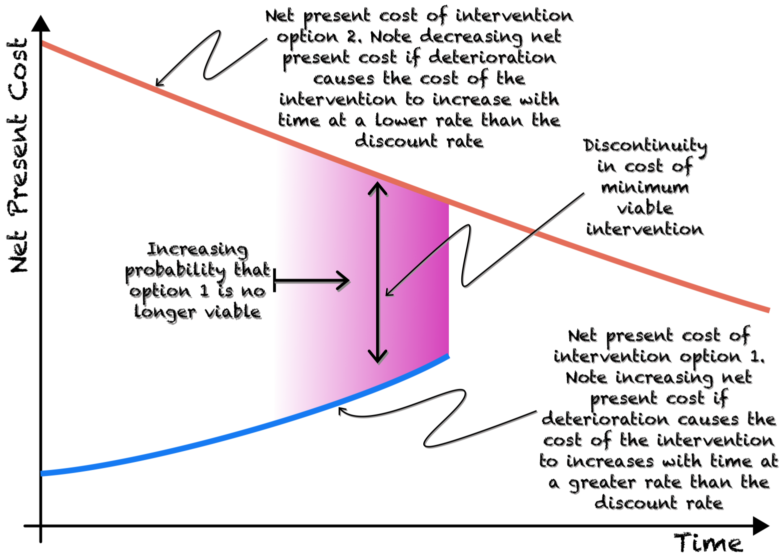

Figure 9.3: Sketch showing the general behaviour of Net Present Cost (at year zero) with time of intervention, for **case b** where the increase in cost of the scheme under consideration per year due to on-going deterioration is higher than the cost of capital (discount rate). Note that in this case, the cheapest time to intervene is as soon as possible.

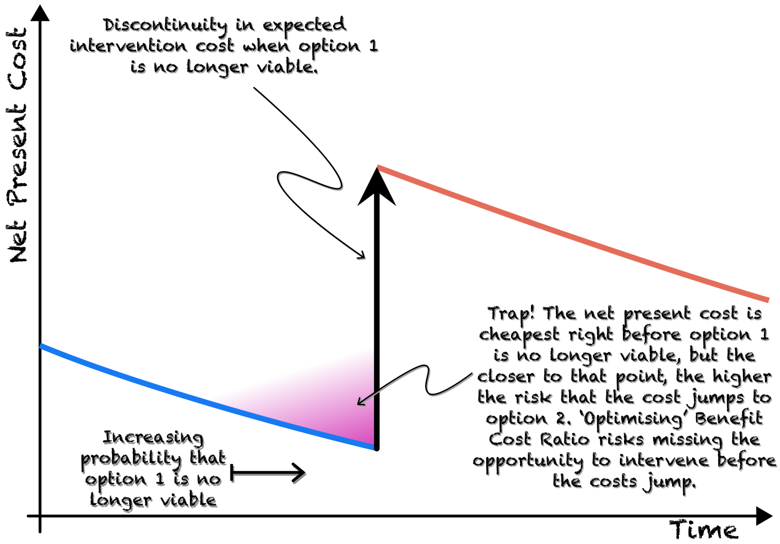

Figure 9.4: In the case where the cost of a maintenance intervention is growing annually at a lower rate than the discount rate, then the year-on-year benefit cost ratio would be zero, and it would appear financially prudent to defer the scheme up until the year in which the proposed intervention isn't expected to be viable the next year. However, there is uncertainty in the timing of this point, and deferral risks a jump in the scheme cost.

The risk posed by the increasing probability of the transition is indicated on the figures by purple shading.

These figures highlight the risk of perpetual deferment of a preventative or corrective scheme - that being that a series of seemingly sensible annual decisions based on low BCRs allow an asset owner to sleep-walk into inaction until a costly and disruptive emergency repair is required. This is particularly the case where the growth in intervention cost is lower than the discount rate used in calculating the BCR. Figure 9.4 shows that choosing the intervention year that would give the lowest net present cost risks missing the point at which a cheaper intervention option is viable.

The case studies in Appendix A give increases in costs of 3.3 times the cost of the initial scheme for a 'corrective' scheme once the initial scheme is no longer viable. If the initial scheme is deffered long enough for an 'emergency' scheme to be required, this was estimated to cost 4 times the initial cost. Considering these two steps and an on-going real-terms annual growth in the cost of the initial scheme, 'engineering judgement' might reasonably suggest that the initial scheme should go ahead as soon as possible. However, rigid processes based on Benefit Cost Ratio, either making a single decision or attempting to maximise the BCR, might result in deferral until emergency. At a systemic level, the result of this could be a huge factor in the annual cost of maintenance.

The consequence of the above observations is that when reviewing intervention schemes they should be categorised by the net rate of growth in cost each year (i.e. if the rate of cost increase due to deterioration per year is greater than the cost of capital). Schemes should then be considered as follows:

Case a Proposed interventions where the annual growth of intervention cost is lower than the cost of capital (Figure 9.2 and 9.4). These should be delayed for as long as possible, but with close attention paid to any possible transitions and the an intervention proactively planned ahead of a transition. Benefit cost ratios for prioritisation should consider the cost of the alternative option following a transition. Condition monitoring could add significant value in these cases.

Case b Proposed interventions where the annual growth of intervention cost is greater than the cost of capital (Figure 9.3). The best timing for these interventions is as soon as possible. They should be prioritised based on a BCR calculated using credible costs and timings for scenarios that take account of future step changes in intervention cost. An exception would be if the net present cost of a future intervention (with a higher current cost) is lower than the current cost of the proposed intervention - in which case deferral may be an option, providing it does not lead to an unacceptable reduction in condition.

In summary:

- The use of Benefit Cost Ratios and whole life costing to make investment decisions appears to be a sound principle in accordance with relevant government requirements.
- Deferral of the same scheme to a future year often generates only a low Benefit Cost Ratio.
- Significant scope change is required to generate a higher BCR, and this could arise from considering ongoing deterioration of an element or structure.
- Considering a family of alternative future scenarios introduces complexity, subjectivity and sensitivity into the process but may be necessary to form an accurate understanding of the true potential future costs. Guidance is necessary to mitigate these issues, and engineering judgement may be the be best way to resolve some decisions.
- Simple considerations based on the rate of growth of costs due to deterioration could provide a useful framework for decisions.

9.3 Deterioration-intervention model for individual structures

9.3.1 Intervention model

Stacy & Bennetts (2014) examined the changes in intervention type and cost with delay period for a series of case studies of common maintenance interventions on highway bridges. Appendix A contains the results, which quantify the cost penalty of deferring maintenance interventions by 5, 10 or 15 years, in comparison to an initial proposed scheme in year 0. The interventions in the study were characterised as an Initial Preventative scheme; a Preventative scheme; a Corrective scheme, and an Emergency/Reactive scheme for intervention options at 0, 5, 10 and 15 years respectively. Results are presented for the Initial Preventative scheme (assumed to grow in scope over time), a Corrective scheme, and an Emergency scheme. For some future years, there are multiple possible intervention options, and it is not known which will be viable at the time.

The behaviour of intervention options in Appendix A, with a number of increasingly costly and disruptive options, has been idealised for use in a stochastic model as a stepped relationship between the condition of an asset and the intervention scale and cost, with four categories of intervention as follows:

A - Initial preventative scheme Represents the minimum viable preventative scheme. The cost is taken to be fixed up to a threshold value.

B - Preventative scheme with ongoing deterioration Represents the extension in scale of the preventive scheme as condition deteriorates. The nature of the intervention is assumed to be the same, but covers a greater area. Beyond the threshold A, the cost is assumed to increase linearly with condition.

C - Corrective scheme Represents a much more major intervention to correct deficiencies that currently impair functionality, or are likely to do so in the near future. Modelled as a fixed cost.

D - Reactive or emergency scheme Represents a scheme that must go ahead immediately to keep the structure in service. Modelled as a fixed cost.

The model accounts for the uncertainty in the types of intervention and the condition/time point when given intervention options are no longer viable.

For each year and each structure, the model determines which intervention type applies using the intervention model set out above, i.e. preventative, corrective or reactive. The intervention types were mapped against the condition index, as shown in Figure 9.5. The performance indicator condition categories (Good / Fair, etc.) are also shown on this figure. As noted in the previous section, there is uncertainty about the boundary between intervention types. It is therefore unrealistic to model this as a hard cut-off. The model therefore uses a probability function around the boundary to determine each year whether the structure changes to the next intervention type. This approach is shown in Figure 9.6.

9.3.2 Cost model

The average of the normalised ratios between the initial scheme and more involved intervention options in the case studies has been used to model the relative costs of the different options. The cost for preventative intervention was assumed to increase as condition deteriorates, reflecting the assumed increasing extent of remedial works. A linear relationship is assumed. Note that the condition measure is not explicitly defined so this relationship is somewhat arbitrary in any case. Corrective intervention is appropriate as condition worsens, with a higher cost. A uniform cost was

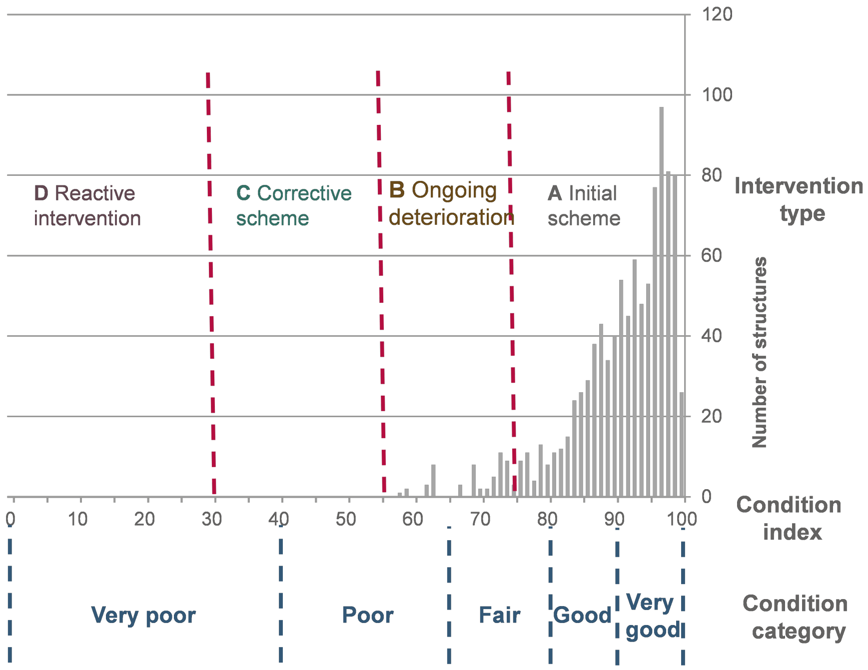

Figure 9.5: Idealised model of the relationship between asset condition and the type of intervention. (background show initial stock condition, which was randomly generated using condition probabilities based on the current condition of Highways England's bridge stock)

assumed regardless of condition. It was assumed once the corrective threshold was passed then major works would be needed to rectify the condition of an entire structural element and hence the costs (including enabling costs) will be largely independent of the actual condition.

Considering again the example from Table A.2, a corrective intervention could involve breakout and recasting concrete over the entire face of an abutment or column. Even if the notional condition measure continues to reduce, once this corrective intervention is required then its scope does not change as it already treats the entire affected element. The highest cost is given for a reactive intervention. In practice, the scope of the reactive scheme may be similar or identical to the corrective scheme (using the example above, the scope would still include treatment of the entire affected structure element). However, the reactive scheme is assumed to cost more due to the unplanned nature of the works giving a cost premium and due to temporary measures needed to ensure the safety of the highway whilst the scheme is designed and mobilised. These could include increased traffic management requirements, such as closure of a hard shoulder for a nominal three months duration whilst the unplanned scheme progresses through design and technical approval. User costs have not been included in this study, and these would tend to increase further the costs associated with reactive schemes in particular.

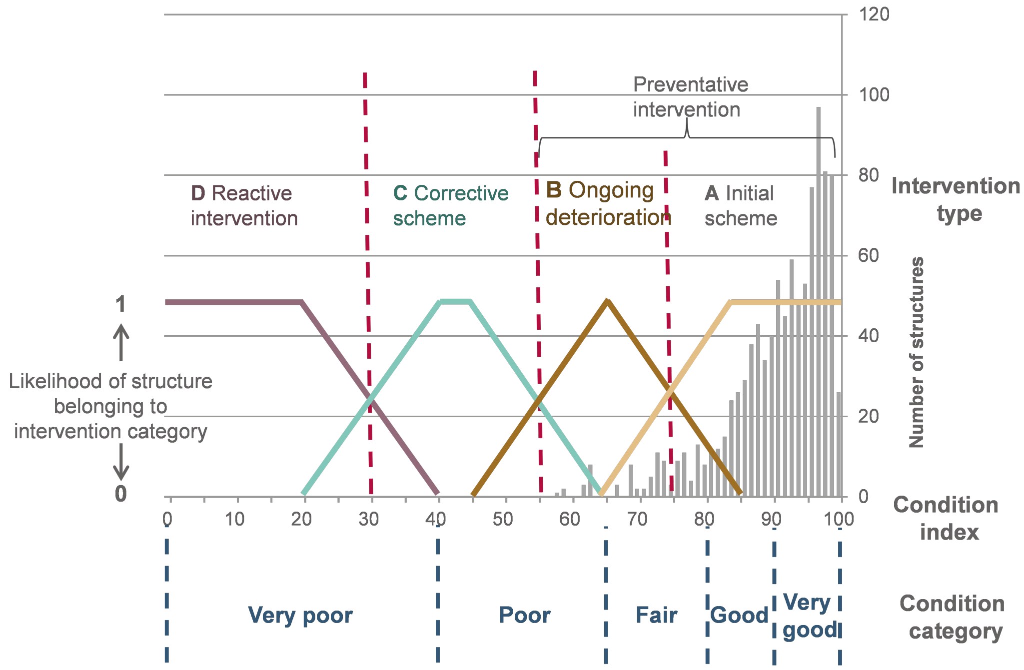

Figure 9.6: Idealised model of the relationship between asset condition and the type of intervention (The background shows initial stock condition, which was randomly generated using condition probabilities based on the current condition of Highways England's bridge stock).

9.3.3 Deterioration model

The model was run in yearly time-steps. At each year, each structure was tested to see if the condition deteriorates and by how much. At the beginning of the simulation, each structure was randomly assigned an annual probability of deterioration. This deterioration probability models variation in the rate at which individual structures deteriorate, and was taken to be constant for each bridge throughout the simulation.

A linear deterioration model was used, thus the change in condition is independent of current condition. Asset condition was modelled on a scale from 100 (perfect) to 0 (failed). The deterioration model was based on simple Markovian deterioration models available in the literature (e.g. Ryall 2010). The Markovian decay parameter defines the annual probability that the asset condition falls. The model assigns an individual Markov decay parameter to each asset randomly between a defined range of annual probabilities between 0.98 and 0.6. Where an asset is predicted to fall in condition in a given year, the condition is deteriorated by either 1, 2 or 3 condition points, which is randomly assigned with equal probability of each. While these values seem arbitrary, in practice variation in these values serves only to adjust the time scale for the simulation, and does not affect the overall behaviour.

As an addition to a traditional Markovian deterioration model, the category of the lowest-cost viable intervention was stored for each asset. Thresholds were set for the transition point between intervention types, with a variability of 20 points to account for the uncertainty in transition from one intervention to another. In each annual cycle the category was reviewed and, if within the variability range of a transition, a random number generator, combined with a probability of transition, was used to decide whether the category was changed. The annual probability of transition was assumed to vary linearly from zero at the edge of the variability range, to unity at the transition threshold.

9.3.4 Sources of uncertainty

There are various sources of uncertainty in the proposed time / cost model, including:

- Uncertainty in initial scheme cost.
- Uncertainty in deterioration rate (and hence cost during the initial 'potential preventative' phase).
- Uncertainty over the time at which the scheme type 'jumps' from a preventative to a corrective intervention with increase in cost.
- Uncertainty over the time at which an emergency intervention becomes necessary.
- Uncertainty over the respective costs of the corrective and emergency interventions.

Each of these sources of uncertainty affect the outcomes of an individual asset, and make it difficult to accurately predict future performance. At a stock-level, some of these uncertainties (such as symmetric cost variation) will average out to result in the mean values, whereas others (such as non-linear jumps in cost) could greatly affect stock-level performance.

9.4 Stochastic model of stock-level behaviour

A model of overall asset stock condition was developed drawing on the single-asset deterioration / intervention / cost model outlined above. The purpose of the asset stock model was to allow the aggregated effect of individual asset decisions on the asset stock to be studied.

Similar models have been developed by others, for example the Structures Toolkit (Atkins, 2015). The model developed in this study is different principally because it attempts to model the Value Management decision process more closely and hence is strongly budget-controlled rather than condition-controlled. In other respects, the model used in this study is more abstract than the Structures Toolkit and it should be taken as representative of the expected behaviours rather than as a predictor of likely costs. The proposed model was been developed using the following steps:

1. Define initial asset stock condition distribution.
2. Define deterioration model for individual assets.
3. Apply categorisation of intervention types as defined by individual structure model.

4. Define intervention / budget decision model.

5. Set up computer model to model asset stock over a number of years.

The computer model was set up using Visual Basic for Applications (VBA) running in Microsoft Excel. The model relies on random number generation and probability functions to simulate:

- Initial structure condition.
- Deterioration rate for each structure.
- Chance of deterioration each year for each structure.
- Likelihood of structure progressing from needing preventative maintenance to corrective and then reactive intervention.

At the heart of the model is a decision process which determines which schemes should be carried out, based on type of intervention required, cost of intervention and available budget. The decision process in the model was set up to reflect the current Value Management Process. The VMR process was idealised as follows:

- All reactive schemes must go ahead, irrespective of budget, because they pose an immediate risk to the safety and operation of the network. In reality, these would be likely to be classified as 'High Safety' schemes.
- All remaining schemes are sorted into a priority list, sorted by intervention category, then by condition. Schemes are selected to go ahead in order of priority, staring with the Category C schemes which would cause the greatest improvement in condition and through the priority list until the budget has been spent.

This decision process is shown graphically in Figure 9.7. For the schemes which are selected to go ahead, the cost is recorded and the structure condition is assumed to be returned to 'Very Good'. The cost of intervention is based on the individual asset model shown in Section 9.3.2 with values taken from the normalised average of case study results.

9.4.1 Initial stock distribution

Data was drawn from Highways England's SMIS system (see Chapter 7) which provides proportions of structures in different condition categories, as indicated in Table 9.1. The condition categories have been aligned with a condition indicator using a scale from 0 - 100, in accordance with the Guidance Document for Performance Measurement of Highway Structures CSS (2007) (See Section 2.4.3).

A random number generator was used to assign an initial condition to each structure considered in the model using a probability density function based on the data held in Highways England's Structures Management Information System (SMIS), for a representative number of structures. The

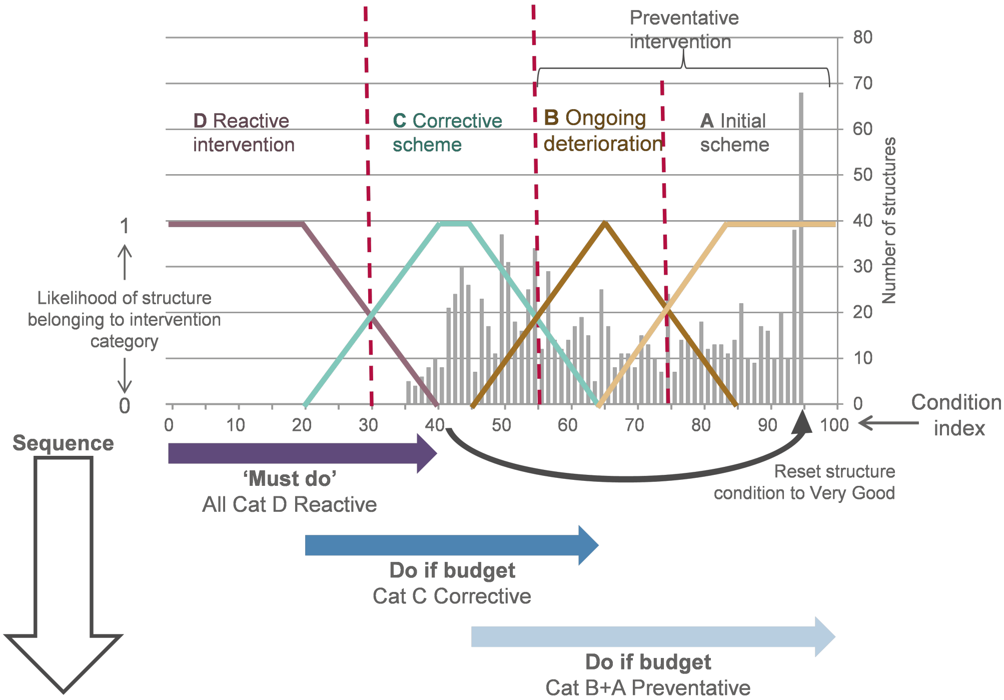

Figure 9.7: Idealised model of the relationship between asset condition, budget and the interventions undertaken.

	Condition Bandings				
Count	Very Good	Good	Fair	Poor	Very Poor
7173	39.50%	47.80%	12.30%	0.40%	0.00%

Table 9.1: Stock level condition scores for all bridges on Highways England's network

selection of a number of bridges was a compromise between calculation times for each scenario and the accuracy of the result. A value of 1000 structures was used in this study, which was determined by increasing the number of bridges used until there was less than 5% variation in the Net Present Value results for each scenario between runs. The initial structure condition is provided with the output results for each scenario in Section 9.7.

While the results of only one simulation are reported for each scenario, the model can be considered to be effectively performing a Monte Carlo simulation for the response of an asset stock to the prescribed funding conditions. This is because the selected number of structures in the model was sufficient to smooth out the results of using randomly generated numbers and probabilities to generate the initial stock, and also to account for both uncertainty in the rate of deterioration and variation in the point of transition between intervention types.

9.4.2 Model outputs

Cost The model records cost incurred each year, broken down by type of intervention. The budget may be exceeded by reactive schemes, since these are considered to pose an immediate safety risk and must be carried out.

Condition The model records structure condition. This is reported as an average and also broken down by condition category.

Intervention Categories The model records the totals for each category of intervention at the end of each year cycle.

9.5 Software process

The overall software simulation operated in the following manner:

Model setup To initialise the model, the following actions are performed:

- Generate a population of bridges.
- Each bridge assigned an initial condition. Initial condition assigned randomly, with PDF defined from actual stock characteristics in SMIS.
- Each bridge randomly assigned a decay probability between a user defined range. This sets the annual likelihood that the condition of the structure will deteriorate. The randomness models the natural variation in the rate of deterioration between structures, for example bridges near salt water might be expected to deteriorate faster.
- Intervention type is initialised.

Yearly Cycle Each year the following are performed (see Figure 9.8):

- The overall budget for the year is set according to a defined budget profile
- Each bridge is stepped over in turn and the following actions taken:

  The bridge's assigned decay rate and a randomly generated number are used to determine if the condition of the structure deteriorates and if so by how many condition points.

  The updated condition is used to decide if the category of maintenance becomes more severe.

  A cost of intervening in the structure this year to return it to full condition is assigned.
- Intervention is undertaken on all bridges that are in Category D.

- The bridges are worked through from Category C up to Category A, performing interventions until the budget has expired.
- The following information is recorded:

  Average condition of the stock this year.

  The cost of maintenance this year.

  The breakdown of the bridge stock by condition and intervention category.

Functionality was also included to ring-fence a portion of funding, to be spent on preventative schemes ahead of all other expenditure.

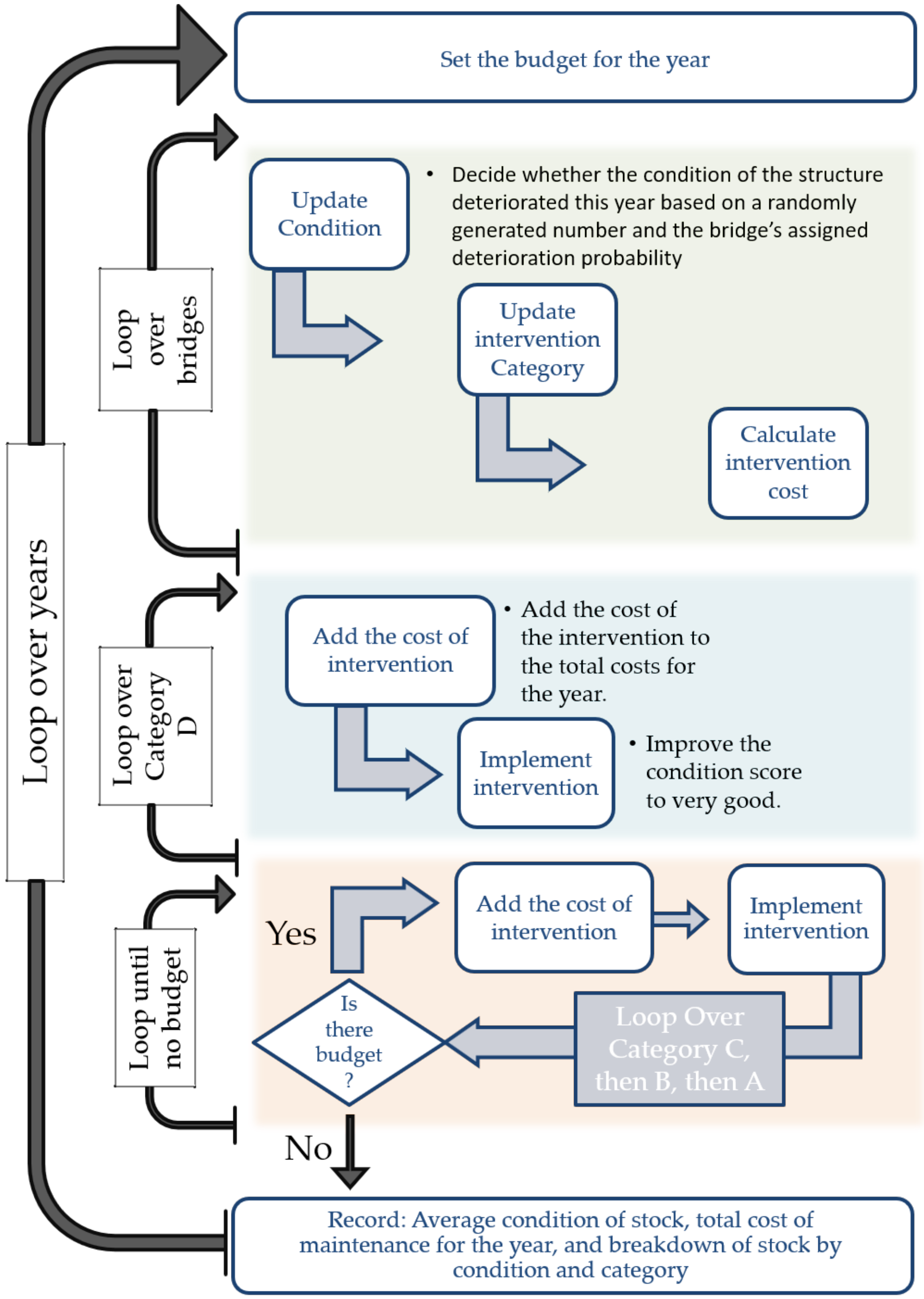

Figure 9.8: Core high-level process loops of the implemented stochastic asset model

9.6 Scenarios

The asset stock model has been run for a variety of scenarios, with the available budget being varied:

A Over funded

B Good funding

C Under funded

D No preventative interventions interventions

E Ring-fenced preventative

The costs used in the simulation have been normalised against the cost of the preventive maintenance intervention and are intended to show comparative behaviours between the scenarios. The reported costs are indicative and are not intended to predict actual costs for the asset stock.

The 'Good funding' level was found by adjusting the annual funding level to the lowest point where the costs never exceeded the allocated budget. For the input parameters used and stock size of 1000, this level of funding was found to be £84 per year. 'Under' and 'Over' funded levels were set at a margin either side of this at £70 per year, and £100 per year, respectively.

The scenarios have been run using cost data from the case studies in Appendix A. It was found that cost data for the individual case studies produced similar behaviours, therefore the average of the four cases was used. The relative intervention costs used are presented in Table 9.2.

Table 9.2: Nominal costs used for intervention options

A - Initial Preventative	B - Limit of ongoing preventative scheme	C - Corrective Scheme	D - Reactive Intervention
£1.00	£1.28	£3.30	£4.03

9.7 Results and discussion

Figures 9.12 to 9.16 show a summary of the stochastic model outputs for each of the scenarios. Each figure presents a dashboard of plots as follows:

Average condition - showing the average condition of the stock under this scenario over the 60yr simulation.

Cost profile - showing the annual expenditure for each year, with the allocated budget (red dashed line).

Cost split over time - a stacked bar chart showing the spending on each intervention type for each year of the simulation.

Condition over time - a stacked bar chart showing the split of the stock by condition categories for each year of the simulation.

Initial and final distribution - showing the initial final distributions of stock condition. These seeds were randomly generated using a probability density function derived from the condition of Highways England's bridge stock.

A consolidated summary for the budget scenarios in Section 9.6 is presented in Figure 9.9, showing average asset condition, and Figure 9.10, showing yearly incurred cost.

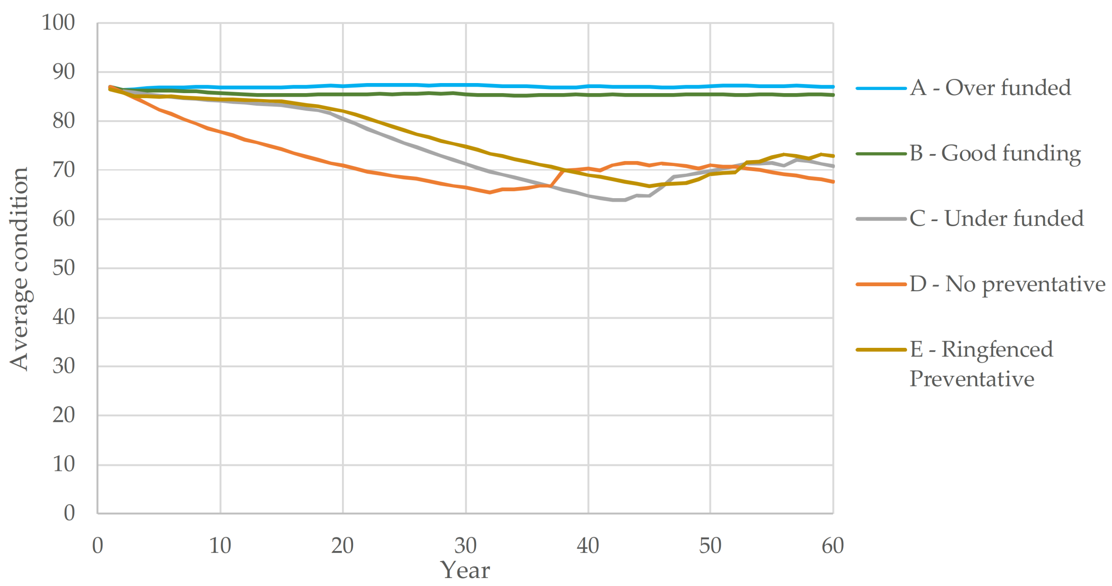

Figure 9.9: Overview of results for average stock condition under all scenarios

The asset stock model was developed to assess the effect of the 'Value Management' type processes, and changes to its application, on overall stock condition. There was a concern that the system of assessing value for money of individual schemes on a structure by structure basis could introduce undesirable effects on the overall stock in the longer term. Of particular concern was the possibility that the implemented method could cause a deterioration of the stock condition over time. Conversely there is the equally undesirable possibility that excessive funding is expended in preserving the stock at a very high standard, where accepting some deterioration before renewal might offer greater value for money. The asset stock model is controlled by the budget, and thus

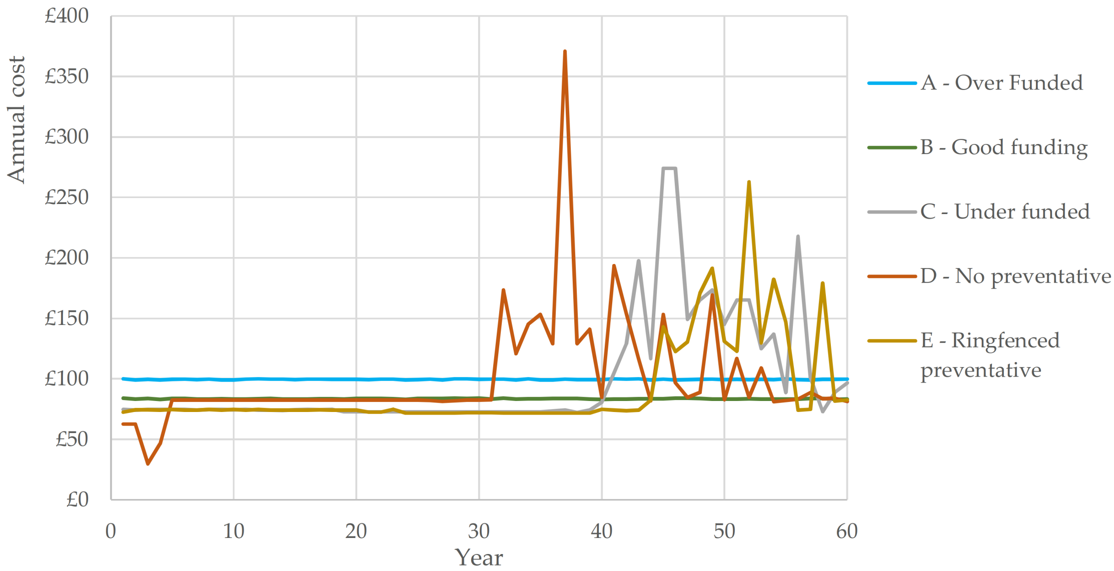

Figure 9.10: Overview of results for annual expenditure all scenarios

reflects the current Value Management process used by Highways England and Transport for London, amongst others. The asset stock model aims to fit corrective and preventative schemes within the available budget. An extract of yearly costs for selected scenarios (taken from Figure 9.10) is presented below in Figure 9.11. This appears to show that all is well, and that in each of these four cases, the available budget is met. However, if the graph is continued for the full length of the simulation, then a different picture emerges (see Figure 9.10). For the under-funded scenario, a dramatic cost increase occurs towards the end of the period. This budget exceedance is generated by reactive schemes which *must* be carried out.

This reflects a potentially serious issue with the Value Management process. We can draw an analogy with a dam storing water, where it is possible to control the volume of water released through the sluice gates. With good intent, we may have instructed the sluice operator that there is an optimum flow rate to send downstream, and the operator may meticulously adjust the sluices to

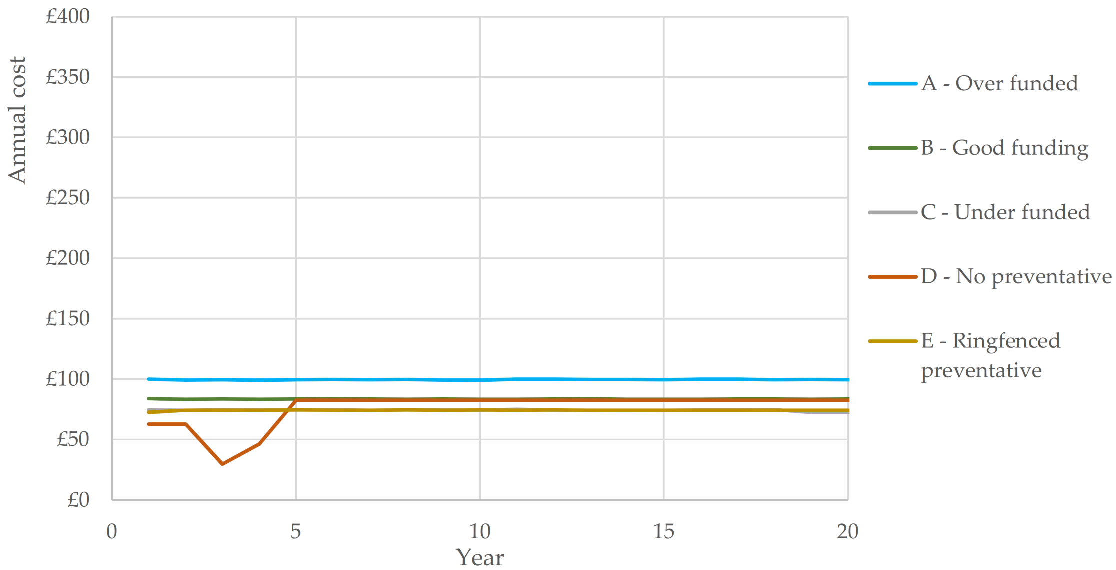

Figure 9.11: Overview of results for annual expenditure all scenarios - showing the first 20 years of the simulation

achieve this flow rate. All appears well, until it is realised that the dam is about to overtop with water and fail, and the operator has no choice but to release large uncontrolled volumes of water to save the dam. The problem is that the real variable which needs to be controlled is the level of water in the dam (the 'maintenance backlog'), rather than the volume released (the 'maintenance budget'). Under the Value Management process, considerable effort is expended on prioritising and selecting schemes to achieve the mandated budget. However, there does not appear to be explicit feedback about the impact of these decisions (and schemes which are not taken forward) on the asset stock condition. Figure 9.9 indicates the effect on average structure condition during the above scenarios. During the first 20 years of the simulation, although all of the scenarios meet the target budget, the under-funded scenarios resulted in a marked deterioration in structure condition. Ultimately, for the under-funded scenario, the condition deteriorates to the extent that reactive intervention is needed for a significant number of structures, leading to the uncontrolled costs.

Figure 9.9 also illustrates generic behaviour found from the model. In particular, the 'elbow' in the condition line (at around year 20 for scenario C) is the point at which most of the budget becomes taken up with corrective maintenance. Due to the higher cost of the corrective maintenance compared with the preventative maintenance, fewer schemes can be carried out. Therefore, on average, the structure condition deteriorates faster from this point since the budget is assumed to be constant and limited. This effect is illustrated in Figure 9.14.

A function was included in the model to allow for the preventative maintenance interventions to be ‘switched off’ altogether, or alternatively, for a certain value of budget to be ‘ring-fenced’ and spent on preventative maintenance rather than other types of intervention. This has been used to explore the effect of preventative maintenance on structure condition and overall yearly cost. Relevant results are presented in Figure 9.15 and Figure 9.16.

Scenario D ‘turns off’ any preventative maintenance. Anecdotally this is an outcome of the current level of budget being assigned through the Value Management process (see Chapters 4 and 5). Compared with the under-funded baseline, turning off the preventative maintenance results in the average structure condition deteriorating more rapidly (Figure 9.9) and the uncontrolled budget exceedance occurring sooner (Figure 9.10). Note that this is despite scenario D being assigned a budget level equal to the ‘Good funding’ of scenario B. Scenario E includes a ‘ring-fenced’ amount of preventative work, thereby prioritising this amount over corrective interventions. Compared with the under-funded baseline, the ‘ring-fencing’ results in a lower net present value of total expenditure, and reduces the amount of budget exceedance. This change is therefore beneficial, since the lower cost of the preventative works allows more schemes to be undertaken.

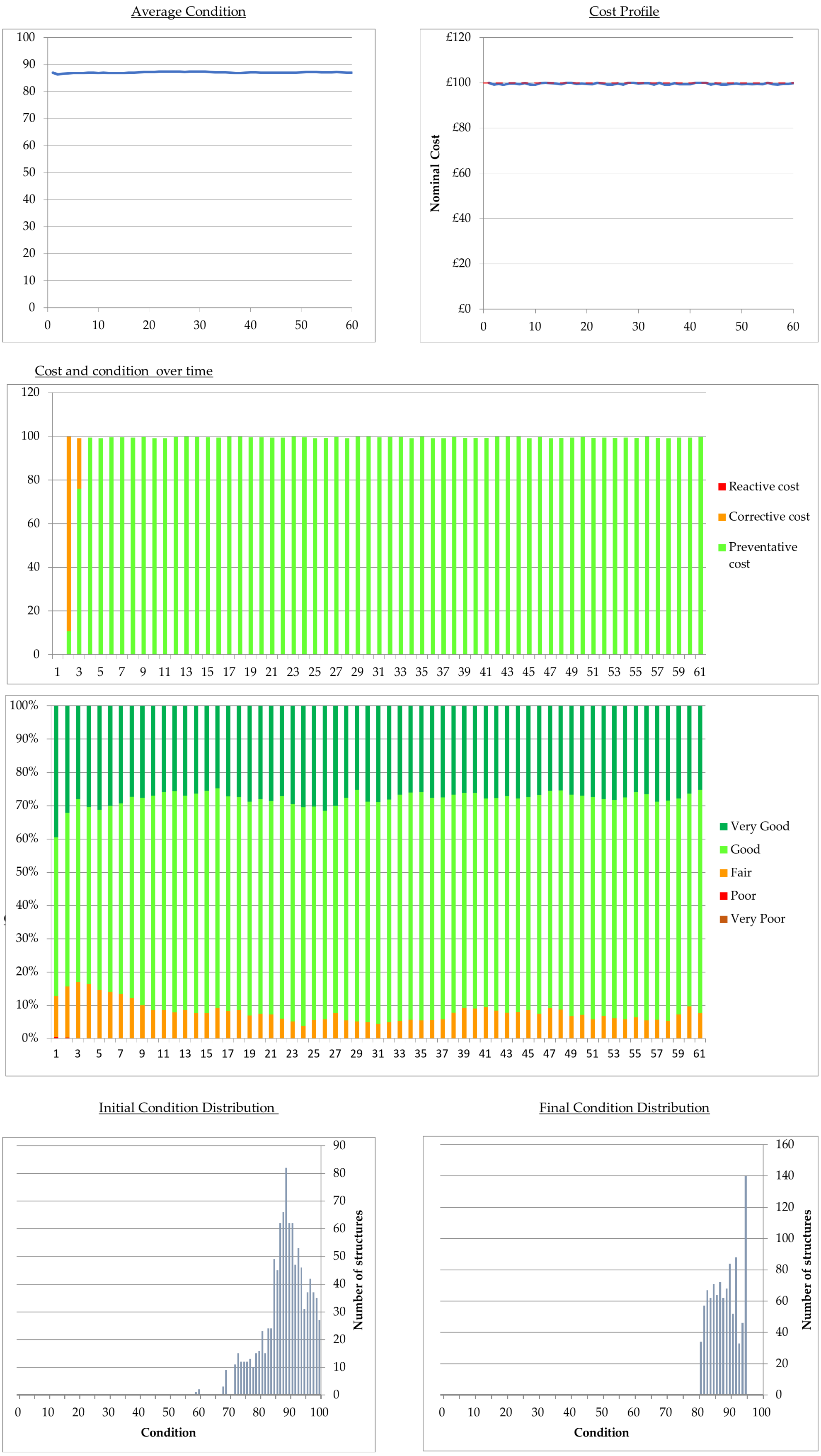

Figure 9.12: Overview of results for scenario A - over funded

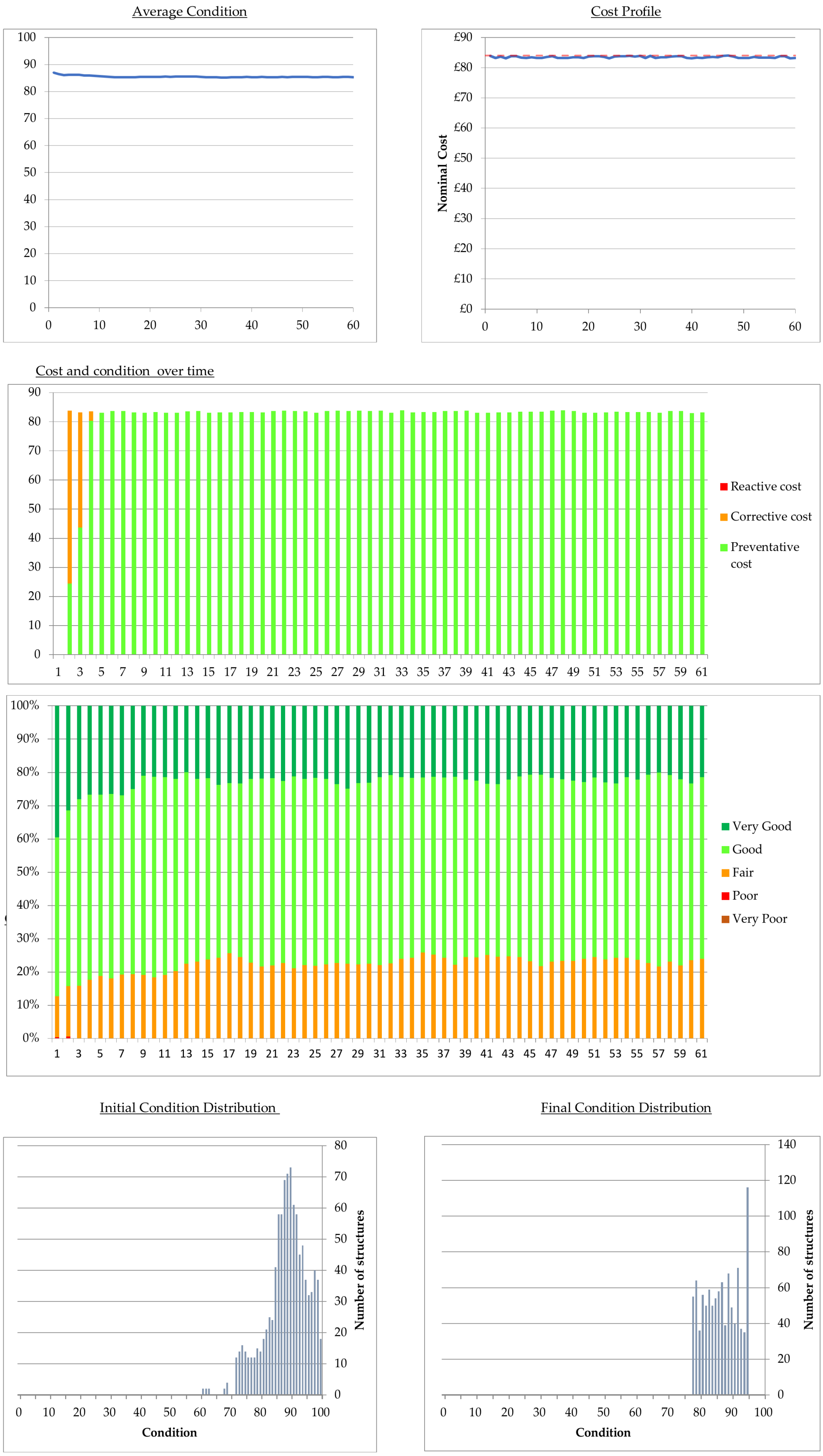

Figure 9.13: Overview of results for scenario B - Good funding

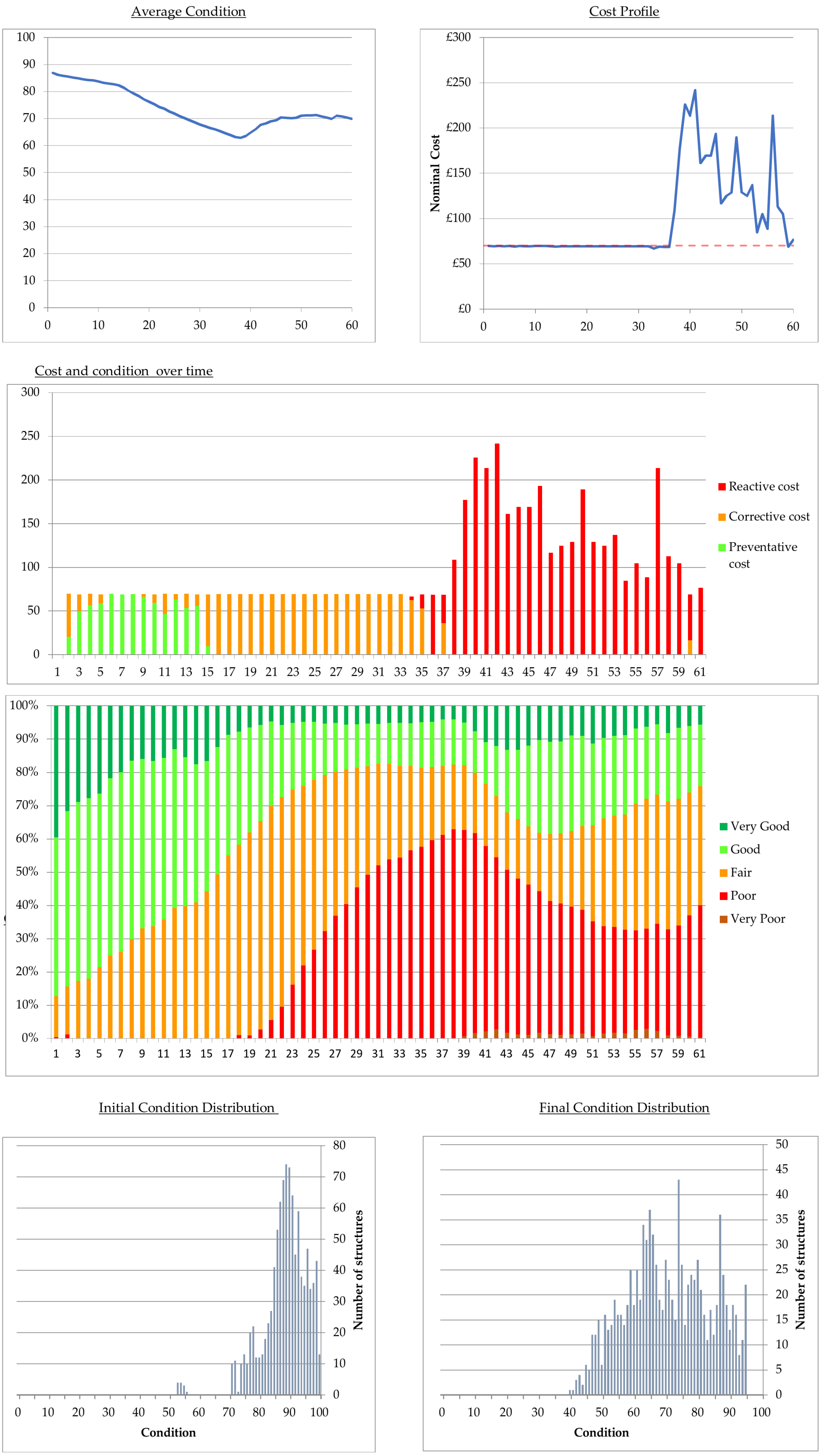

Figure 9.14: Overview of results for scenario C - Under funded

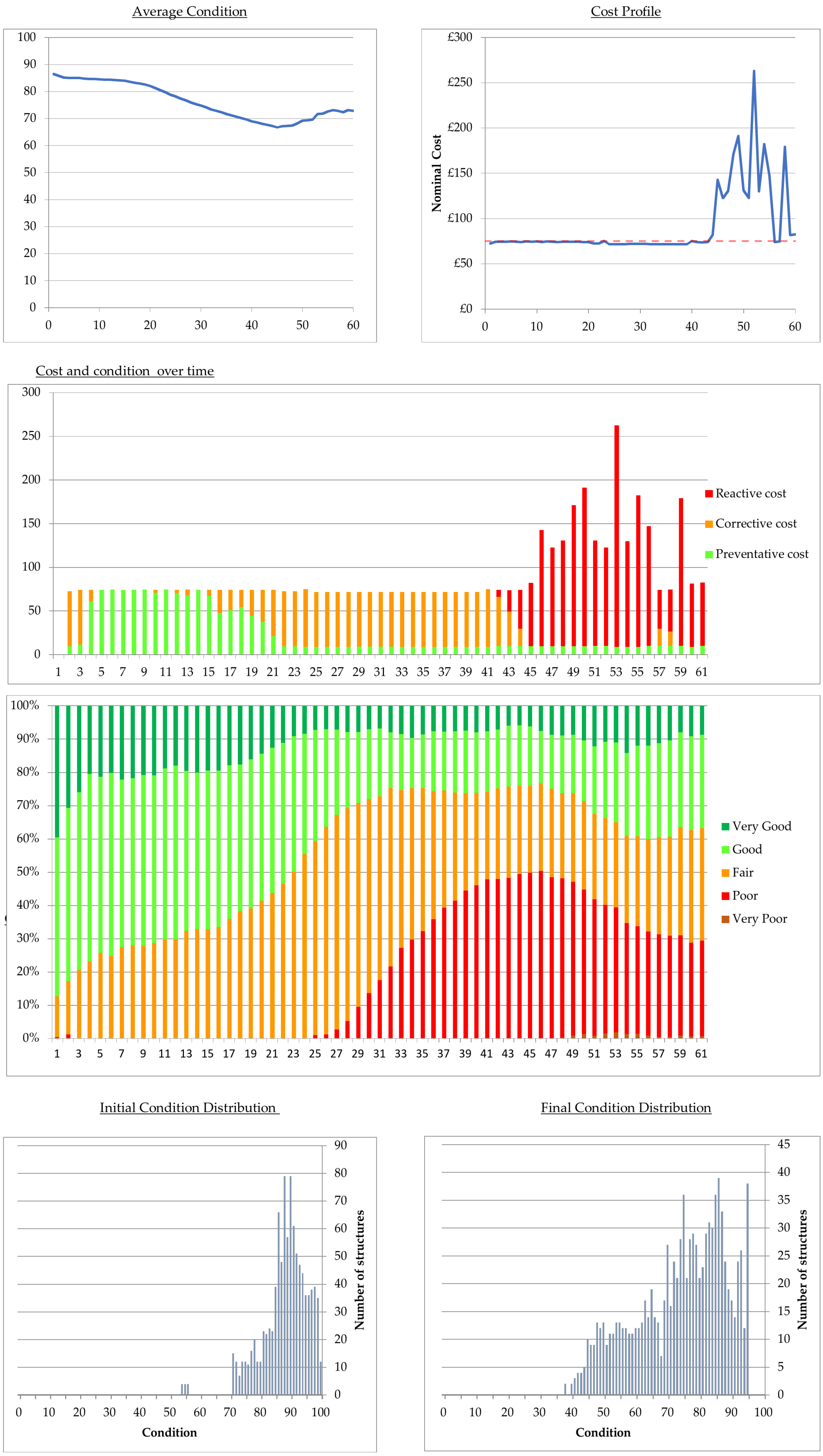

Figure 9.15: Overview of results for scenario D - Underfunded with ringfenced preventative maintenance

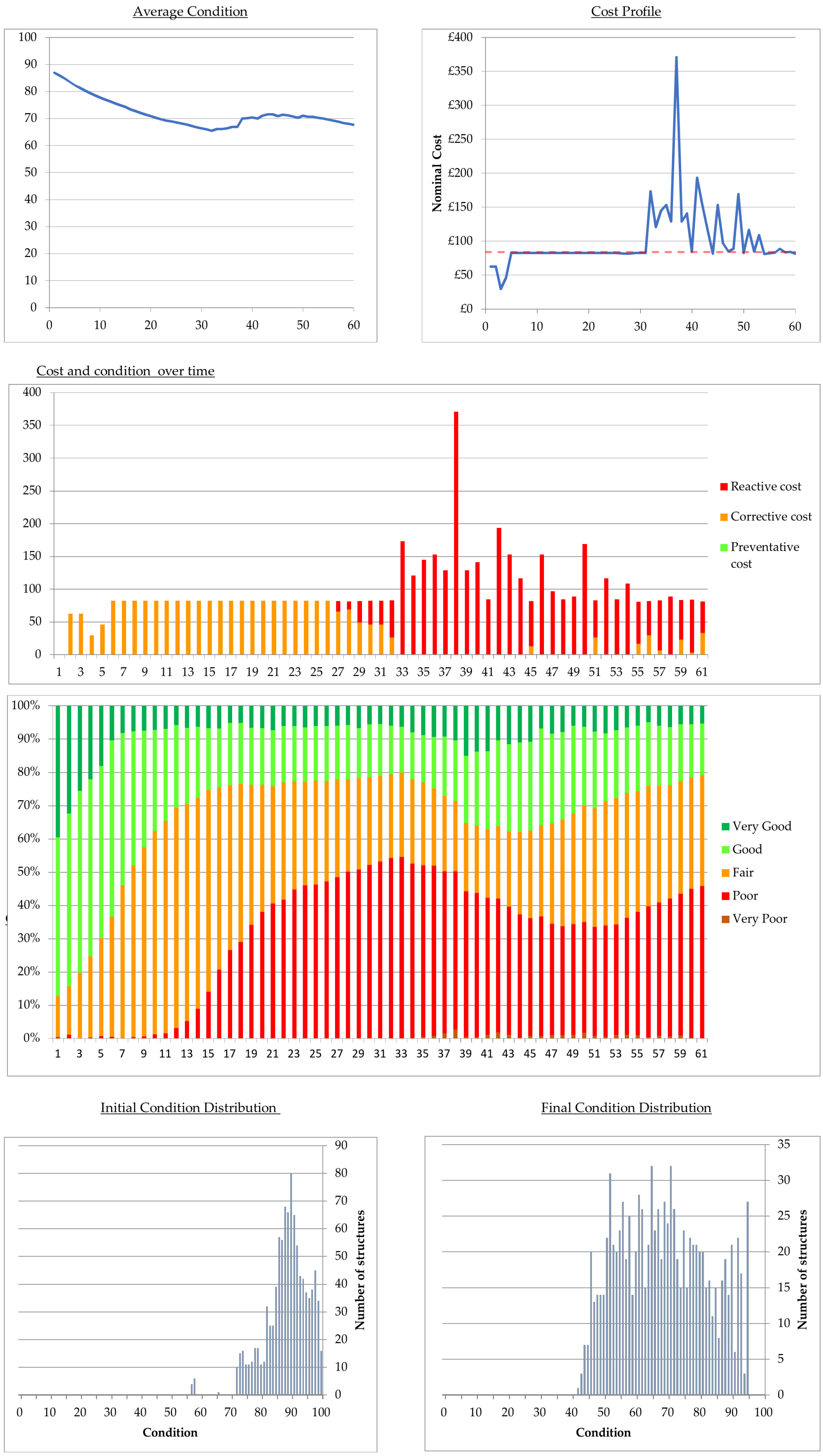

Figure 9.16: Overview of results for scenario E - No preventative maintenance

9.7.1 Limitations of the model

The single asset model has limitations; in particular, it only considered a single element on a structure.

There is currently no central source of data on deterioration / replacement rates. Unless and until this becomes available, the calculation of whole life costs and BCRs by asset managers will remain subjective and must be based on experience and judgement. The process requires assumptions of deterioration rates, assumptions of work required in future to address scheme and assumed timescales, particularly for transitions between viable options.

The nature of the BCR calculation means that the BCR value can be maximised by proposals which do not necessarily make most effective use of resources considering the structure as a whole and the asset stock as a whole. In particular, the highest BCR result is generated by maximising the scope difference between Year 0 'do something' and the 'do minimum' / 'future do something'; work scopes which are the same in both scenarios will tend to reduce the BCR value. Therefore, this may incentivise schemes to focus only on remedial works to one affected element rather than carrying out holistic programme of works to structure. This could lead to missed efficiencies with procurement, traffic management and scheme set-up.

9.8 Concluding remarks

Key findings from the asset stock model are summarised as follows:

- A decision-making process which concentrates exclusively on budget can conceal issues with the deterioration of the overall asset stock condition.
- A downward trend in asset stock condition can create a backlog of problems, potentially leading to unavoidable and significant future cost increases.
- Once a large proportion of work becomes reactive then control is lost over the budget, as most of the works become 'must-do'.
- The lowest NPV over the study period was produced by a steady state level of good funding which maintained the asset stock in a generally good condition.
- Strategies including preventative maintenance produced better results (i.e. better average asset condition and lower costs) than strategies excluding preventative maintenance, even in situations where the budget was highly constrained. Anecdotal evidence (e.g. chapter 5) suggests that the level of funding available in recent years through the current Value Management process has led to little or no preventative works being carried out.

The above discussion raises concerns that the Value Management process does not explicitly address the cumulative effect of decisions related to individual assets on the overall asset stock condition. To address this it is recommended that consideration of overall asset stock condition is taken into account in setting forward budgets for asset management organisations.

Chapter 10

Summary and Conclusions

10.1 Overview

This thesis:

- Records the current industry practice for bridge management in the United Kingdom through a series of interviews and workshops.

- Develops a conceptual model of the bridge management system and uses it to target areas for further study.

- Presents a case study into the role of stakeholders in asset decision making systems, which highlights the need to consider the human aspects of the system as well as the mathematical.

- Identifies visual inspection as the primary form of condition monitoring on bridges in the United Kingdom, and presents one of the largest ever undertaken programmes of study into the reliability of visual inspection data.

- Demonstrates the application of machine learning and data analysis techniques to the visual inspection data held by bridge owners, and identifies interesting trends in the condition, rate of change of condition and construction quality of bridges on Highways England's network. For example it is noted that, contrary to common assumptions, newer bridges deteriorate faster than older bridges, and that the quality of bridge construction in the United Kingdom appears to be falling, after a peak in the late 1980's.

- Finally, uses numerical modelling to predict the system-level response of bridge stocks to asset-level decision making.

10.2 Opportunities for paradigm shifts in bridge management

In carrying out the above work, three opportunities have been identified for a paradigm-shift in current practice to enable more effective bridge management:

1. **A shift in asset decision making systems to ask the question '*when is the optimum time to intervene*', rather than '*should we intervene now*'. This should be coupled with the observation that the '*optimum*' timing of a maintenance intervention is governed by the rate of growth of the cost of the option for each year it is delayed, relative to the cost of capital.**

   In the United Kingdom, organisations are required to 'discount' the cost of future expenditure as part of the decision making processes using approaches such as benefit cost ratios, whole life cost and lifecycle cost analyses. For the vast majority of components or structures, the 'optimum' time to intervene with maintenance is either:

   1. As soon as possible - applied in cases where the annual percentage growth in costs due to deterioration is greater than the discount factor.
   2. Immediately before the current intervention option is no longer viable - applied in cases where the growth in costs is lower than the discount factor.

   In the second situation, where the growth in cost is lower then the discount rate and it makes sense to delay the intervention for as long as practical, it can be crucial to avoid deterioration beyond a point where the current intervention option is no-longer viable. Deterioration modelling and structural health monitoring could have great value in such cases.

2. **A shift in condition monitoring to focus on rate of change in condition, rather than current condition state.**

   Visual inspection is the most common from of condition monitoring for bridges in the United Kingdom. However, the low frequency of inspections, coarse condition recording scales and uncertainty due to variability between inspectors, means that there is too much uncertainty for inspection results to be used to monitor the rate of change of condition. However, understanding the rate of change in condition is fundamental to sucessful bridge management.

3. **A shift to focus on monitoring condition and maintenance backlog would give a better control on spending than a focus on cost alone.**

   A focus on spending within short-term budgets risks spending too much or too little, with no feedback to ensure spending is neither excessive, nor building up problems for the future. Implementing controls so that a stock is maintained in a steady good condition with preventative maintenance can reduce expenditure in the long-term.

10.3 Limitations and future work

The following limitations in the work are noted:

- While international literature is reviewed, the work presented in this thesis focuses on the management of bridges in the United Kingdom. It is anticipated that many of the findings would be of direct relevance to bridges managed in other countries, however there would be value in further study to broaden the scope.
- The stochastic modelling presented in chapter 9 assumes all assets follow a similar behaviour of condition and intervention types with time. While it is considered that this is a good model for bridge components, there would be value in developing the model to include alternative profiles.
- Many of the case studies and datasets are based in a single organisation (Highways England). While efforts have been made to confirm that the results can be applied to other organisations in the UK (particularly through the interviews presented in Chapter 4) there would be merit in extending the work to other organisations.
- It is identified that a change in focus in bridge condition monitoring to focus on recording the rate of change, rather than condition state, is required. Further work is needed to establish and verify methods for recording the rate of change.

10.4 Summary of conclusions and impacts

The following key conclusions and impacts have been presented:

- Models have been established and gaps filled in the literature regarding current practice in bridge management in the UK.
- The uncertainty in bridge condition data has been quantified, and the impacts of uncertainty on the that data for bridge management have been evaluated.
- The work has shown that materials testing results do not usually provide significant additional condition information that would result in changes to the defect scores allocated by inspectors following visual inspections. (Note that the value of materials testing in designing remedial action for defects is not assessed).
- The work has demonstrated the potential for modern data science techniques to deliver value from the data held by bridge management organisations.
- The work has demonstrated the need for a change in focus of bridge inspections to place much greater emphasis on change in condition. It is likely these recommendations will be

incorporated into the next generation of standards for Bridge Inspection at Highway Bridges in the United Kingdom.

- The work has identified deficiencies in typical models of bridge deterioration and intervention cost, and decision strategies to avoid them. The key conclusion is that organisations should aim to maintain assets in a steady state of good repair, rather than maintain steady spending.
- The work has identified a required re-structuring of asset decision making processes to clearly distinguish stages of 'needs identification', 'prioritisation' and 'value engineering', and to maintain, but manage, the positive contribution of engineering judgement. These recommendations have been implemented in Highways England's new Value Management system, and are being adopted across their supply chain.

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Appendix A

Intervention Case Studies

A.1 Acknowledgement

Appendix A describes the work of Mungo Stacy of WSP UK Ltd and is presented in an internal WSP report to the Highways Agency (Stacy & Bennetts, 2014). The work was assisted by John Bennetts and has been included here to facilitate discussion and inclusion of the results within this thesis.

A.2 Introduction

To quantify the magnitude of the variations in intervention costs between different options, a series of real-world case studies on Highways England's network were developed and costed.

A.3 Methodology

Case studies were selected from works previously submitted for funding under Highways England's 'Value Management' decision making process. For each case study, a series of scenarios were developed in discussions with the managing agents. The scenarios were based on the experience of the agent in managing their structure stock and similar projects which had been required over the year. The scenarios are intended to give examples credible interventions which could be required in the event of continued deferral of works (i.e. repeated year-on-year 'Do Minimum'). To provide a framework for discussion and to explore the transitions in intervention type and cost with time, the maintaining agents we asked to consider the likely interventions required after 5, 10 and 15 years of defferal as follows:

Intervention A was defined as the reference scheme, i.e. the actual scheme which had been submitted through the Value Management Process in a previous year, assumed to be progressed immediately (year 0).

Intervention B envisaged that works would be deferred for the short term, but a scheme would be progressed in Year 5. Over these timescales, it was envisaged that the reference scheme would still be applicable. However, continued deterioration would lead to an increase in extent of the defects, and an appropriate increase in quantities was proposed in discussion with the managing agent.

Intervention C assumes that the works are deferred for an extended period with an intervention progressing in the medium term at Year 10. At this time it was considered that the original scheme may not be viable and that an alternative type of scheme would be necessary. Discussions were held with the managing agent about an appropriate type of intervention.

Intervention D considered that no interventions were made, until at Year 10 an emergency repair became necessary. In general the scope of works was similar to the Case C alternative scheme. However, an uplift on cost would be applied due to the unplanned nature of the works.

Summaries for each of the case studies are included in Tables A.2 to A.5. The scope for each of the case study scenarios was priced by a Quantity Surveyor working for WSP Ltd, familiar with highway scheme pricing. The quantity surveyor also allocated an assumed cost variation against the estimate. The estimates were cross-checked against the experience of the managing agent and their experience of the overall level of pricing of similar schemes, and showed close agreement.

Table A.1: Details of Case Studies

Case study	Nature of defect	Description of defect
1	Concrete spalling	Spalling to concrete piers
2	Half joint	Cracking and spalling at half joints
3	Scour	Scour adjacent to pier
4	Waterproofing	Surfacing failures due to failed waterproofing

Table A.2: Details of Case Study 1

Scenario	Nature of defect	Scope of intervention
1a	Spalling concrete to 4 piers x 3 support locations	185 m^2 concrete repair (remove loose concrete, surface preparation, repair material 100mm depth). Adjacent lane closures for 12 week scheme duration.
1b	Assume existing defect has developed over 15 years, hence over a further 5 years there is a proportionate 33% increase in the scope of the repair works.	245 m^2 concrete repair (remove loose concrete, surface preparation, repair material 100mm depth). Adjacent lane closures for 16 week scheme duration
1c	Spalling and reinforcement corrosion developed to extent that required to encase piers with new concrete.	240 m^3 new concrete encasement. Adjacent lane closures for 20 week scheme duration
1d	Delamination of concrete risks spalled concrete falling onto the carriageway.Emergency repairs required due to safety issue. Work scope same as scenario 1c.	240 m^3 new concrete encasement. Safety lane closure for 12 weeks during scheme design and approval. Emergency propping for same duration. Lane closures for 20 week scheme duration. Uplift on costs due to reactive work

Table A.3: Details of Case Study 2

Scenario	Nature of defect	Scope of intervention
2a	Spalling concrete to faces of half joints (4 locations)	15 m^2 concrete repair. Night work. Night lane closures with traffic in Lane 3 only for 4 week scheme duration.
2b	Assume 50% increase in spalling extent over 5 years	22.5 m^2 concrete repair. Night work. Night lane closures with traffic in Lane 3 only for 6 week scheme duration.
2c	Assume reinforcement in half joint suffered corrosion due to water ingress through cracks. Assume need reinforcement embedment and repair on concrete shelf.	Propping to relieve load. Remove surfacing & joints. Rebar and concrete repair to half joints. Replace surfacing joints. Contraflow (4+1) to allow propping and work on joint, 16 weeks total.
2d	Sudden deterioration of structure and opening of cracks observed under monitoring. Traffic restricted on road above, and same works as scenario 2c required, but urgently.	Work scope same as scenario 2c. Safety lane closure for 12 weeks during scheme design and approval. Emergency propping for same duration. Closure of minor road crossing bridge. Contraflow (4+1) to allow propping and work on joint, 16 weeks total. 20% uplift on costs due to reactive work.

Table A.4: Details of Case Study 3

Scenario	Nature of defect	Scope of intervention
3a	Erosion of river bank - gabion basket solution. Difficult access - assume materials lowered from bridge deck.	2 x 35 linear m gabion baskets 3 m high and 150 m^3 backfill. Hard shoulder closures to allow for access, 4 week scheme duration.
3b	Assume 50% increase in erosion extent over 5 years, same solution as 3a.	2 x 50 linear m gabion baskets 3 m high and 225 m^3 backfill. Hard shoulder closures to allow for access, 5 week scheme duration.
3c	Assume erosion starting to undermine pilecap. RC wall required to train river. Mass concrete to make good below pilecap.	New RC wall 2 x 50 m long, 4 m high, with 1600 m^3 backfill in volume behind wall. 50 m^3 mass concrete around pilecap. Hard shoulder closures to allow for access, 10 week scheme duration.
3d	Sudden undermining of pile cap during flood event. Highway restricted until the same works as 3c have been completed.	Work scope same as scenario 3c. Lane closure to reduce loading on bridge for 12 weeks during scheme design and approval. Lane closures for 10 week scheme duration. 20% uplift on costs due to reactive work.

Table A.5: Details of Case Study 4

Scenario	Nature of defect	Scope of intervention
4a	Surfacing failure due to failed interface between waterproofing layers. Rewaterproof and resurface bridge deck.	2 spans x 30 m length x 18 m width = 1080 m^2 waterproofing and surfacing.Assume contraflow for 2 weekends.
4b	Final scheme same as 4a. Assume 2% patch repairs required each year.	1080 m^2 waterproofing and surfacing. Patch repairs 20 m^2 / year x 5 years. Assume contraflow for 2 weekends.
4c	Final scheme same as 4a. Assume 2% patch repairs required each year. Assume local concrete repairs needed to deck due to hammer of traffic in potholes.	1080 m^2 waterproofing and surfacing Patch repairs 20m2 / year x 10 years. Concrete repairs 20 m^2. Contraflow needs to be maintained for 7 days each carriageway for concrete to cure - 14d contraflow.
4d	In 15 year timeframe, unlikely that waterproofing failure will lead to structural failure. Similar to 4c but greater extent of concrete repair.	1080 m^2 waterproofing and surfacing. Patch repairs 20 m^2 / year x 15 years. Concrete repairs 50 m^2. Contraflow needs to be maintained for 7 days each carriageway for concrete to cure - 14d contraflow.

A.4 Results

The intervention costs for each of the case studies are summarised in Table A.6, Table A.7 gives the intervention costs in terms of net present value at year 1. The net present values have been calculated using a discount rate of 3.5%, which is specified for use in UK government decision making (HM Treasury, 2018, Chapter 2). Discount rates are used to account for the preference to spend money later rather than sooner. The Treasury discount rate takes into account interest rates, inflation and social costs.

Each of the case studies shows a significant increase in cost between the initially proposed scheme and a corrective scheme, and then again a second significant increase from the corrective scheme to an emergency on. The discounting effect reduces the size of these jumps, however the discounting does not fully compensate for the jumps in cost - a much higher discount rate would be required before it was cheaper (in NPV terms) to wait for the more expensive interventions in these case studies. There is an exception in case 4, where the Net Present Value (NPV) of the deferred initial scheme is lower than the initial scheme cost, this is because the rate of increase of the scheme cost is lower than the discount rate. For this waterproofing example, either the scheme would not be justifiable on a WLC basis, or a longer-term than 15yr period may need to be considered to see benefits. Alternatively, the scheme would be viable if the discount rate was reduced.

Table A.8 presents the ratio of the costs (in current / net present terms) of the intervention options relative to the initial (year 0) scheme cost. The final ratios highlight the penalty of allowing an asset to deteriorate to a point where a reactive scheme is necessary - it may cost over five times as much than the cost of undertaking preventative works earlier (or three times in real-terms).

Table A.6: Intervention costs for case studies (Costs given in 2016 values at the year of the intervention)

Scenario	Intervention A: Initial scheme	Intervention B: Preventative	Intervention C: Corrective	Intervention D: Reactive	Assumed variation in cost
Case 1: spalling	£415,868	£553,802	£777,525	£1,198,661	20%
Case 2: half joint	£108,720	£160,423	£371,702	£589,656	30%
Case 3: scour	£301,718	£384,976	£996,002	£1,216,131	30%
Case 4: waterproofing	£149,334	£166,182	£214,822	£263,833	25%

Table A.7: Net present intervention costs for case studies (discounted at 3.5%)

Scenario	Intervention A: Initial scheme Year 0	Intervention B: Preventative Year 5	Intervention C: Corrective Year 10	Intervention D: Reactive Year 15
Case 1: spalling	£415,868	£465,194	£552,043	£719,197
Case 2: half joint	£108,720	£134,755	£263,908	£353,794
Case 3: scour	£301,718	£323,380	£707,161	£729,679
Case 4: waterproofing	£149,334	£139,593	£152,524	£158,300

Table A.8: Ratio of intervention option costs to initial intervention option. Values given for current costs, and for net present costs

Scenario	Intervention A: Initial scheme Year 0	Intervention B: Preventative Year 5	Intervention C: Corrective Year 10	Intervention D: Reactive Year 15
Case 1: spalling	1	1.33 / 1.12	1.87 / 1.33	2.88 / 1.73
Case 2: half joint	1	1.48 / 1.24	3.42 / 2.43	5.42 / 3.25
Case 3: scour	1	1.28 / 1.07	3.30 / 2.34	4.03 / 2.42
Case 4: waterproofing	1	1.11 / 0.93	1.44 / 1.02	1.77 / 1.06

Appendix B

Interview protocol

Bridge Management Practice

Facilitated Model Building and Semi Structured Interview Protocol

Research Title

The Management of Bridges

Research Purpose

This research seeks to understand the processes involved in bridge management. Particularly, the research is interested in the way in which decisions are made and the data that is collected and used to support these decisions.

Intended outcomes from interview

The interview and will gain a qualitative perspective of the way in which individual stakeholders perceive the processes involved in the management of bridges. Where relevant it will gain an understanding of data that are collected in the stakeholder's organisation and the way these data are recorded and processed. It will explore the links between decision making and data.

Facilitated hierarchical process model building will be used to draw out the stakeholder's perspective on the bridge management system and the processes it is made up of. Stakeholders will be asked to rate their confidence in each process using an Italian Flag notation. The individual models from stakeholders will be synthesised to build an over-arching model of the bridge management system that included all the individual perspectives.

Ethics

All participants will sign a consent form for agreeing to take part in the study, which will be recorded and transcribed for analysis. The recording will not be circulated wider than the study team.

Responses will me anonymised for publication and participants retain the right to withdraw statements at any time up to publication.

Format

The interview will last for approximately one hour, with participants being asked to respond to questions grouped into the following themes:

- Introduction
- Collection of asset data
- The use of asset data
- The decision making process
- The overall processes involved in managing bridges

The interview will be recorded on a digital device and the interviewer will also take notes to assist during the interview.

Facilitated Hierarchical Process Modelling Session

Participants will be provided with a short read-ahead including an example hierarchical process model for the water industry and Italian flags for a managing Dams. In the session, participants will be provided with A3 sheets of paper with the initial root of a process model, showing the process “managing bridges” in the context of “delivering highways”.

The modelling is split into two stages:

1. Participants will be asked to think about the processes and sub processes that comprise the UK’s bridge management system by answering the question “*how?*” to identify sub processes for each node, noting that reading upwards should answer the question “*why?*”.
2. Once the participants are content that they have identified all the processes, they will be asked to rate how well we, as an industry, perform at each of the leaf node processes. “*Do we do that well, or poorly, or do we just not know?*”

Interview questions

Introduction		
1	What is your role?	
2	What does your role involve on a day to day basis?	
3	How long have you been in your current role?	

Collection of asset data		
4	What data do you collect on your bridge assets?	
5	How do you collect these data?	

Use of asset data		
6	How do you use the data that you collect on your structures?	
7	Are there any IT systems that you use to manage and analyse your data?	

The decision making process		
8	How do you make decisions regarding the management of structures?	

The overall process of managing bridges		
9	Hierarchical Process Modelling exercise.	See A3 Sheet(s)
Open question		
10	Looking at the model we've produced, which aspects of your role keep you up at night?	

Appendix C

Supporting materials for stakeholder workshops

C.1 Questionnaire

Questionnaire on renewals projects prioritisation (VM Review)

Introduction

Value Management is the system used by Highways England to prioritise renewal work. The current system has evolved over the last 15 years. The transformation to the Strategic Highways Company has driven a need to review the Value Management Process in the light of the obligations on Highways England, in particular, the license and the Roads Investment Strategy Performance Specification.

A consultation is being held to gather evidence from stakeholders of the Value Management system, to inform the development of updates to, or replacement of, the current system. The consultation is being led by Professional & Technical Solutions, supported by WSP Parsons Brinckerhoff.

In order to collect the view of selected stakeholders on the Value Management system and potential future development or replacement by alternative systems, please can you complete the following questionnaire. For specific information on the project please read the Briefing Paper attached.

Glossary

- RPP – the term ‘RPP’ is used throughout to refer to the future Renewals Project Prioritisation process.
- VM – the current Value Management process.
- RIS – Roads Investment Strategy

Questionnaire on renewals projects prioritisation (VM Review)

Instructions for completion

There are three tables to complete:

Table 1: General information
Please complete the table by providing the general information required.

Table 2: Statements
Please rate your level of agreement with each of the statements listed in the table on a scale of 1-9, with *(1) strongly disagree*, *(5) neither agree or disagree*, *(9) strongly agree*. You may also enter comments relating to your answer in the right hand column of the table. You may complete electronically or by hand.

Table 3: Open questions
Please provide answers to the open questions listed in the table. These questions will be discussed further at the workshops.

It is not expected that you spend long on each question – your initial reaction is likely to be the most accurate.

Responses will be used to shape the workshops to which you have been invited and are therefore requested by 2 November 2015.
Please send responses to Mungo Stacy (stacym@pbworld.com).

Questionnaire on renewals projects prioritisation (VM Review)

Table 1: General information

Name:	
Organisation:	
Role in the organisation:	
Key areas of interest in Value Management Please specify	

Assumptions

Some elements of any new RPP process are required by the Highways England Licence and therefore it is assumed that the new RPP process should:

- Support Highways England's organisational objectives;
- Provide robust arrangements to demonstrate value for money is achieved;
- Enable Highways England to demonstrate efficiency savings.

Questionnaire on renewals projects prioritisation (VM Review)

Table 2: Statements about renewal projects prioritisation – please score 1-9

		Strongly disagree				Neither agree or disagree				Strongly agree	
No.	**Statement**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Comment**
CURRENT VALUE MANAGEMENT (VM) PROCESS – TO WHAT EXTENT DO YOU AGREE WITH THESE STATEMENTS?											
1.	The current VM process demonstrates that investments are made in the right areas.										
2.	The right solutions are being put forward under the current VM process.										
3.	The current VM process achieves value for money.										
4.	The current VM process discriminates effectively between schemes.										
5.	It is necessary to manipulate the current VM process to ensure the selection matches what engineering judgement would suggest.										
6.	The current VM process is manipulated to suit commercial drivers.										
7.	The current VM process is efficient in terms of staff time.										
8.	The focus on the 'do minimum' option under the current VM process is effective at keeping assets safely operational for a minimal budget.										
9.	The focus on the 'do minimum' option under the current VM process is effective at achieving the lowest whole life cost.										

Questionnaire on renewals projects prioritisation (VM Review)

Table 2: Statements about renewal projects prioritisation – please score 1-9

		Strongly disagree				Neither agree or disagree				Strongly agree	
No.	**Statement**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Comment**
10.	Highways England's high level objectives under the RIS performance specification are fully satisfied by the current VM selection criteria.										
11.	Roles and responsibilities for asset ownership are clearly defined.										
FUTURE RENEWAL PROJECTS PRIORITISATION (RPP) PROCESS – TO WHAT EXTENT DO YOU AGREE WITH THESE STATEMENTS?											
12.	There is a clearly defined need for a framework that ranks and prioritises renewals work.										
13.	The new RPP process should rank and prioritise a list of specific individual projects.										
14.	The new RPP process should provide robust arrangements to demonstrate value for money is achieved.										
15.	The new RPP process should implement a whole life cost approach to managing the assets.										
16.	The new RPP process should enable appraisal of options for short or long term costs in line with government policy.										
17.	The new RPP process should enable value to be realised from the assets.										
18.	The new RPP process should allow flexibility to incorporate future changes to Highways England's business priorities.										

Questionnaire on renewals projects prioritisation (VM Review)

Table 2: Statements about renewal projects prioritisation – please score 1-9

No.	Statement	1 (Strongly disagree)	2	3	4	5 (Neither agree or disagree)	6	7	8	9 (Strongly agree)	Comment
19.	The priorities for the RPP process should not need to be amended during the current RIS period.										
20.	Funding for all maintenance works should be determined by applying the new RPP process.										
21.	Small value works should not be subject to the same RPP process.										
22.	The new RPP process should operate as part of an overall asset management system.										
23.	The prioritisation of work through the new RPP process will effectively constitute the asset management plan.										
24.	A wide range of factors need to be considered in prioritising work.										
25.	The prioritisation should be driven by a definitive and prescriptive scoring system.										
26.	The prioritisation should allow for the judgment of experienced engineers.										
27.	The prioritisation should provide consistency with regional asset objectives.										
28.	The prioritisation should provide consistency with national asset objectives.										
29.	The prioritisation should be considered in the context of the programme or portfolio of asset renewals.										

Questionnaire on renewals projects prioritisation (VM Review)

Table 2: Statements about renewal projects prioritisation – please score 1-9

No.	Statement	1 Strongly disagree	2	3	4	5 Neither agree or disagree	6	7	8	9 Strongly agree	Comment
30.	The prioritisation should be based solely on the merits of individual projects.										
31.	The new RPP process should promote additional work carried out as part of proposals where these can reduce or eliminate long term costs or disruption.										
32.	The new RPP process should justify paying more for higher quality if the whole life cost is better.										
33.	The new RPP process should encourage savings during the design process.										
34.	The new RPP process should achieve cost-certainty once schemes have been selected.										
35.	The new RPP process should develop a pipeline of future maintenance.										
36.	Schemes which address an urgent safety concern should be prioritised separately from preventative maintenance.										
37.	The new RPP process should allow for reactive spending where it represents good value for money.										
38.	Maintenance agents should have freedom to select and use appropriate commercially available asset-management tools.										
39.	The new RPP process should include tools to support decisions.										
40.	The same tools should be used across all regions.										

Table 2: Statements about renewal projects prioritisation – please score 1-9

		Strongly disagree				Neither agree or disagree				Strongly agree	
No.	**Statement**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Comment**
41.	The project prioritisation should be considered across all regions.										
42.	The new RPP process should be an incremental change from the current VM process.										
43.	The new RPP process should take less resource to operate than the current VM system.										

Table 3: Open questions

No.	Question	
CURRENT VM PROCESS – OPEN QUESTIONS		
1.	What do you think is the overall purpose of the current VM process?	
2.	How effective do you think the current VM system is in prioritising the right works?	
3.	What features of the current VM process work well, are particularly important, or should not be lost in future revisions?	
4.	How well does the current VM scoring system discriminate between schemes? Which aspects are well discriminated? Which aspects are poorly discriminated?	
5.	How effective are the existing whole life cost analysis tools (PEAT / SWEEP)?	
6.	Where has it been useful or necessary to apply local knowledge under the current VM process?	
7.	To what extent do the current levels of cost and performance data support meaningful whole life cost predictions?	
8.	Any other comments?	

Table 3: Open questions

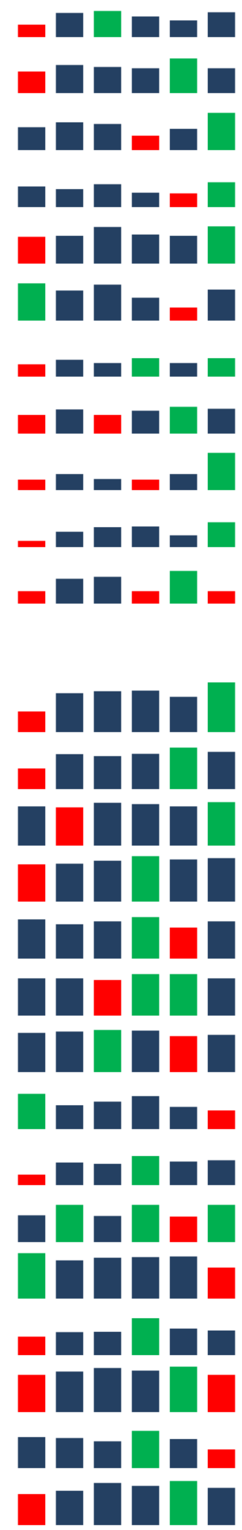
No.	Question	
FUTURE RENEWAL PROJECTS PRIORITISATION (RPP) PROCESS – OPEN QUESTIONS		
9.	What should be the objective of the new RPP process?	
10.	What timescales for work planning should be covered by the new RPP process?	
11.	To what extent should Highways England and Agents respectively be involved in maintenance decisions?	
12.	What should be the future roles and responsibilities for asset management?	
13.	Should there be a distinction between work prioritisation and asset management in general?	
14.	Should the focus of the new RPP process be on taking decisions or providing evidence to justify decisions?	
15.	What are the most important features in prioritising renewals projects?	
16.	Any other comments?	

C.2 Questionnaire Analysis

Qn #	Question	HE - NDD AIG	HE - NDD AIG	HE - NDD AIG	HE - NDD ADM	HE - NDD ADM	HE - NDD ADM	HE - NDD ADM	HE - NDD ADM	HE - NDD ADM	HE - NDD ADM	HE - NDD ADM	HE - NDD ADM	HE - NDD ADM	HE - NDD ADM
	CURRENT VALUE MANAGEMENT (VM) PROCESS – TO WHAT EXTENT DO YOU AGREE WITH THESE STATEMENTS?														
1	The current VM process demonstrates that investments are made in the right areas.	5	2	2	6	6	4	3	3	5	4	7	2	7	7
2	The right solutions are being put forward under the current VM process.	6		3	6	7	5	5	1	5	8	6	3	8	7
3	The current VM process achieves value for money.	8	2	4	6	7	4	5	1	5	8	7	6	6	5
4	The current VM process discriminates effectively between schemes.	7	2	4	8	4	3	3	1	5	6	4	2	2	5
5	It is necessary to manipulate the current VM process to ensure the selection matches what engineering judgement would suggest.	2	7	7	6	8	7	6	8	5	2	6	3	4	5
6	The current VM process is manipulated to suit commercial drivers.	7	7	7	7	5	7	5	9	5	2	6	8	5	5
7	The current VM process is efficient in terms of staff time.	5		1	7	4	3	1	1	7	5	4	3	3	3
8	The focus on the 'do minimum' option under the current VM process is effective at keeping assets safely operational for a minimal budget.	8	2	2	6	1	7	2	2	5	8	7	3	8	5
9	The focus on the 'do minimum' option under the current VM process is effective at achieving the lowest whole life cost.	4	2	2	3	1	2		2	5		4	4	8	3
10	Highways England's high level objectives under the RIS performance specification are fully satisfied by the current VM selection criteria.	3	2	1		2	3	3	2	5	3	5	5	5	2
11	Roles and responsibilities for asset ownership are clearly defined.		5	1	5	6	5	1	2	5	3	6	6	8	8
	FUTURE RENEWAL PROJECTS PRIORITISATION (RPP) PROCESS – TO WHAT EXTENT DO YOU AGREE WITH THESE STATEMENTS?														
12	There is a clearly defined need for a framework that ranks and prioritises renewals work.	5	7	1	3	9	8	6	9	7	9	6	9	9	5
13	The new RPP process should rank and prioritise a list of specific individual projects.	5	2	6	4	6	8	5	7	5	9	5	9	8	7
14	The new RPP process should provide robust arrangements to demonstrate value for money is achieved.	8	7	7	8	7	8	5	8	1	9	6	9	9	9
15	The new RPP process should implement a whole life cost approach to managing the assets.	6	8	7	8	9	6	5	8	1	9	7	9	8	8
16	The new RPP process should enable appraisal of options for short or long term costs in line with government policy.	7	8	7	7	7	8	5	7	1	9	7	9	5	7
17	The new RPP process should enable value to be realised from the assets.	6	8	7	7	7	8	5	7	1	9	7	9	9	8
18	The new RPP process should allow flexibility to incorporate future changes to Highways England's business priorities.	7	8	7	8	8	9	8	8	1	7	7	9	9	9
19	The priorities for the RPP process should not need to be amended during the current RIS period.	6	6	8	8	2	2	5	5	5	9	6	5	5	1
20	Funding for all maintenance works should be determined by applying the new RPP process.	1	5	2	5	7	4	1	1	5	9	5	6	7	1
21	Small value works should not be subject to the same RPP process.	5	3	8	9	8	7	8	9	6	3	8	8	2	9
22	The new RPP process should operate as part of an overall asset management system.	8	8	9	8	8	7	5	7	3	9	7	8	9	8
23	The prioritisation of work through the new RPP process will effectively constitute the asset management plan.	2	3	7	8	5	5	1	1	3	2	7	8	7	5
24	A wide range of factors need to be considered in prioritising work.	6	8	7	8	7	8	9	9	2	5	9	9	8	9
25	The prioritisation should be driven by a definitive and prescriptive scoring system.	7		5	6	5	6	3	7	2	9	7	5	9	5
26	The prioritisation should allow for the judgment of experienced engineers.	7	8	3	8	8	8	6	9	4	1	8	7	8	5

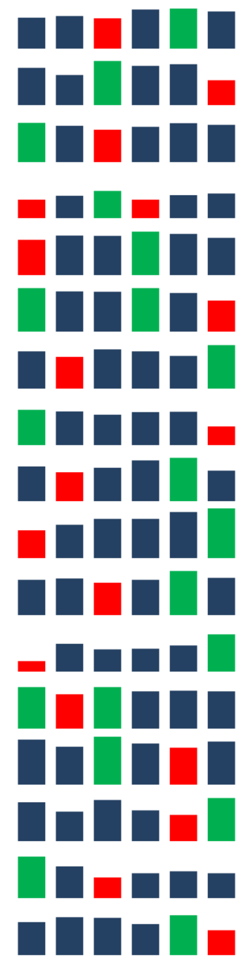
Qn #	HE - PTS	HE - PTS	HE - PTS	HE - PTS	HE - PTS	HE - PTS	HE - PTS	HE - PTS	HE - PTS	HE - Other	HE - Other	HE - Other	ASC Contractors	ASC Contractors	ASC Contractors	ASC Contractors	ASC Contractors	ASC Contractors	ASC Contractors	ASC Contractors	ASC Contractors	DBFO
1	8	4	6	2	5	3	5	7	7	6	5	2	3	6	2	7	3	2	6	2	2	5
2	8	3	6	5	4	5	5	4	7	5	5	5	7	7	6	6	8	8	7	8	2	5
3	6	3	6	5	3	5	6	6	7	2	4	4	3	5	5	6	3	2	6	5	5	7
4	6	3	2	2	7	4	5	6	7	3	4	3	1	4	3	5	2	2	4	2	6	5
5	8	7	7	8	8	7	7	7	3	7	5	5	9	4	2		3	7	4	7	8	7
6	5	7	7	5	8	6	8	8	7	1	7	6	4	5	1		7	1	1	1	5	6
7	5	5	1	2	1	2	2	6	5	4	5	3	3	3	5	4	3	2	4	2	3	4
8	1	3	3	1	5	2	6	8	7	6	5	3	7	2	3	7	5	5	6	5	8	5
9	1	3	1	2	2	4	3	4	5	1	5	2	4	2	5	4	1	5	4	1	6	7
10	3	2	3	4	3	5	4	6	8	1	7	5	1	4	5	3	1	2	5	2	3	5
11	8	3	1	5	9	5	4	4	9	1	5	3	7	5	7		6	5	7	6	7	3
12	5	7	8	8	7	7	9	8	9	9	8	6	9	7	8	7	5	5	7	5	7	9
13	8	5	6	7	8	7	4	4	8	8	6	6	9	7	6	9	8	8	7	8	7	7
14	8	8	9	5	8	9	7	9	8	9	9	5	9	5	7	9	8	8	7	8	5	8
15	8	5	9	5	8	9	6	9	9	9	8	8	7	8	7	9	9	8	7	9	6	8
16	8	5	9	3	8	7	6	9	8	9	8	6	9	8	6	2	2	7	4	8	8	7
17	8	7	7	3		8	7	9	5	9	9	5	9	5	9	7	8	7	7	9	8	7
18	8	7	8	7	8	8	9	8	7	9	7	7	9	6	7	3	7	7	6	9	7	7
19	8	5	1	5	5	5	6	9	5	6	8	5	4	6	5	3	6	5	4	6	2	4
20	5	7	7	3	1	1	5	3	8	6	5	6	9	5	5	5	4	5	5	4	1	5
21	4	4	2	8	9	2	5	8	5	7	7	7	1	7	8	3	5	5	3	5	9	7
22	8	6	9	5	9	7	8	8	8	8	8	7	9	8	5	9	7	8	8	8	8	6
23	8	5	2	1	1	5	7	6	8	8	5	8	6	5	3	9	3	3	7	4	8	5
24	8	8	9	9	9	8	9	6	7	9	7	7	9	7	9	9	8	9	6	9	9	7
25	3	5	8	2	1	7	7	9	6	8	7	6	4	4	2	9	6	7	7	6	6	4
26	9	5	9	9	7	6	9	8	8	9	7	6	9	7	9	7	9	9	6	8	9	7

Qn #	Responses	Mean	Std Dev	Agreement	HE - NDD AIG (3 No.)	HE - NDD ADM (11 No.)	HE - PTS (9 No.)	HE - Other (3 No.)	ASC Contractors (9 No.)	DBFO (1 No.)
1	36	4.47	1.92	Neutral	3.00	4.91	5.22	4.33	3.67	5.00
2	35	5.60	1.78	Neutral	4.50	5.55	5.22	5.00	6.56	5.00
3	36	4.94	1.72	Strong Neutral	4.67	5.45	5.22	3.33	4.44	7.00
4	36	3.94	1.82	Neutral	4.33	3.91	4.67	3.33	3.22	5.00
5	35	5.89	1.97	Neutral	5.33	5.45	6.89	5.67	5.50	7.00
6	35	5.46	2.26	Weak Neutral	7.00	5.82	6.78	4.67	3.13	6.00
7	35	3.46	1.63	Strong Disagreement	3.00	3.73	3.22	4.00	3.22	4.00
8	36	4.69	2.28	Weak Neutral	4.00	4.91	4.00	4.67	5.33	5.00
9	34	3.29	1.77	Disagreement	2.67	3.56	2.78	2.67	3.56	7.00
10	35	3.51	1.71	Strong Disagreement	2.00	3.50	4.22	4.33	2.89	5.00
11	34	5.03	2.24	Weak Neutral	3.00	5.00	5.33	3.00	6.25	3.00
12	36	7.03	1.86	Agreement	4.33	7.27	7.56	7.67	6.67	9.00
13	36	6.64	1.65	Strong Agreement	4.33	6.64	6.33	6.67	7.67	7.00
14	36	7.47	1.71	Strong Agreement	7.33	7.18	7.89	7.67	7.33	8.00
15	36	7.50	1.66	Strong Agreement	7.00	7.09	7.56	8.33	7.78	8.00
16	36	6.69	2.08	Agreement	7.33	6.55	7.00	7.67	6.00	7.00
17	35	7.17	1.78	Agreement	7.00	7.00	6.75	7.67	7.67	7.00
18	36	7.39	1.59	Strong Agreement	7.33	7.55	7.78	7.67	6.78	7.00
19	36	5.17	1.98	Neutral	6.67	4.82	5.44	6.33	4.56	4.00
20	36	4.56	2.27	Weak Neutral	2.67	4.64	4.44	5.67	4.78	5.00
21	36	5.94	2.39	Weak Neutral	5.33	7.00	5.22	7.00	5.11	7.00
22	36	7.53	1.34	Strong Agreement	8.33	7.18	7.56	7.67	7.78	6.00
23	36	5.03	2.43	Weak Neutral	4.00	4.73	4.78	7.00	5.33	5.00
24	36	7.83	1.48	Strong Agreement	7.00	7.55	8.11	7.67	8.33	7.00
25	35	5.71	2.12	Neutral	6.00	5.82	5.33	7.00	5.67	4.00
26	36	7.28	1.85	Agreement	6.00	6.55	7.78	7.33	8.11	7.00



27	The prioritisation should provide consistency with regional asset objectives.	4	8	6	8	7	6	6	8	4	1	8	9	5	7	5	1	9	6	1	7	9	8	7	8	8	6	9		7	5	8	8	6	8	9	7
28	The prioritisation should provide consistency with national asset objectives.	7	8	6	6	5	6	5	4	4	1	8	9	9	7	8	9	9	6	9	7	9	8	8	8	8	6	9		6	9	8		6	8	7	5
29	The prioritisation should be considered in the context of the programme or portfolio of asset renewals.	8	8	6	6	6	7	5	8	4	7	7	9	8	8	8	5	9	6	1	7	5	7	8	8	9	3	9		7		7	7	6	7	8	7
30	The prioritisation should be based solely on the merits of individual projects.	6	2	4	6	3	2	1	4	5	7	5	6	7	5	8	5	5	6	9	4	5	4	3	7	2	3	1		5		7	5	4	6	5	5
31	The new RPP process should promote additional work carried out as part of proposals where these can reduce or eliminate long term costs or disruption.	4	8	8	8	8	8	9	8	5	8	9	9	9	0	7	6	9	7	9	7	7	8	6	9	8	7	8	7	8		7	8	7	8	8	7
32	The new RPP process should justify paying more for higher quality if the whole life cost is better.	8	8	8	8	6	8	9	8		9	6	9	7	5	8	5	7	7	9	8	7	8	8	9	8	7	7	8	8	9	5	7	6	6	9	6
33	The new RPP process should encourage savings during the design process.	5	8	8	8	2	8		3	1		9	9	7	8	8	5	9	6	6	8	7	9	8	9	8	4	8	5	7		6	5	6	5	8	8
34	The new RPP process should achieve cost-certainty once schemes have been selected.	5	8	7	7	7	6	6	8	1		8	9	7	5	8	5	5	6	3	7	6	6	7	8	8	3	9	5	5		8	5	6	5	8	4
35	The new RPP process should develop a pipeline of future maintenance.	6	8	6	7	8	7	5	1	1	1	8	9	9	7	8	5	3	8	5	9	6	8		8	8	7	9	7	8	9	8	8	7	9	8	6
36	Schemes which address an urgent safety concern should be prioritised separately from preventative maintenance.	5	6		8	7	8	9	7	1	1	8	5	7	9	8	5	2	9	9	8	8	9	8	8	8	6	9	8	9	9	9	8	7	8	9	9
37	The new RPP process should allow for reactive spending where it represents good value for money.	7	8	5	8	7	8	5	8	1	8	8	6	9	8	1	5	7	8	7	8	7	8	5	8	8	4	9	8	8	9	8	8	7	8	8	7
38	Maintenance agents should have freedom to select and use appropriate commercially available asset-management tools.	5	2	1	5	4	6	5	9	1	9	7	5	6	3	5	5	1	7	9	4	5	3	2	8	4	2	1	5	5	1	7	8	4	8	8	7
39	The new RPP process should include tools to support decisions.	7	7	9	7	8	8	5	5	1	6	7	9	8	8	5	5	9	7	9	8	8	9	9	8	8	5	9	8	3	7	8	7	7	7	8	7
40	The same tools should be used across all regions.	8	8	9	7	9	8	9	4	1	9	6	9	9	8	9	9	9	7	9	9	9	9	9	9	8	6	9	8	8	7	6	5	7	5	8	8
41	The project prioritisation should be considered across all regions.	5	8	9	6	8	8	5	4	1	9	8	8		1	9	9	9	6	3	8	8	9	8		9	3	2		2	7	5	7	6	6	7	8
42	The new RPP process should be an incremental change from the current VM process.	7	7	9	5	7	6	9	6	1	5	7	8	8	5	5	3	3	6	1	5	7	2	7		5	5	9	6	5	3	5	6	3	6	5	5
43	The new RPP process should take less resource to operate than the current VM system.	5	5	9	7	7	7	9	9	1	5	8	8	8	9	6	5	9	9	7	9	7	8	3		6	6	5	5	7	9	8	8	8	8	9	5
	Completion	98%	93%	98%	98%	100%	100%	95%	100%	98%	93%	100%	100%	98%	100%	100%	100%	100%	100%	98%	100%	100%	100%	98%	93%	100%	100%	100%	88%	100%	81%	100%	98%	100%	100%	100%	100%
	Average	5.8	5.9	5.6	6.7	6.1	6.3	5.2	5.5	3.3	6.1	6.8	7.0	7.1	5.9	6.5	5.2	6.0	5.5	6.0	6.2	6.5	7.0	6.8	6.9	6.7	5.1	6.6	5.8	5.8	6.5	6.0	6.0	5.8	6.2	6.7	6.2
	Std Dev	1.7	2.5	2.7	1.4	2.1	2.0	2.4	3.0	2.0	3.0	1.3	2.3	1.9	2.5	2.2	1.8	3.0	2.3	3.0	2.1	1.7	2.0	1.8	2.6	1.7	1.7	2.9	1.7	2.2	2.5	2.3	2.2	1.5	2.3	2.2	1.4
	Average variation from mean	1.8	1.7	2.1	1.5	1.6	1.1	2.0	2.4	4.0	3.1	1.3	1.8	1.9	2.1	2.0	1.8	2.2	1.8	2.6	1.3	1.2	1.9	2.0	1.9	1.3	1.7	2.3	1.1	1.8	2.1	1.6	1.5	1.4	1.6	1.8	1.3

27	35	6.54	2.18	Weak Agreement	6.00	6.27	5.89	7.33	7.50	7.00
28	34	7.00	1.83	Agreement	7.00	5.82	8.11	7.33	7.57	5.00
29	34	6.79	1.73	Strong Agreement	7.33	6.82	6.22	6.67	7.29	7.00
30	34	4.76	1.88	Neutral	4.00	4.64	5.44	4.00	4.71	5.00
31	35	7.40	1.69	Strong Agreement	6.67	7.36	7.33	8.00	7.63	7.00
32	35	7.46	1.20	Strong Agreement	8.00	7.50	7.44	8.00	7.22	6.00
33	33	6.70	2.05	Agreement	7.00	6.11	7.33	7.00	6.25	8.00
34	34	6.21	1.80	Neutral	6.67	6.40	5.89	6.33	6.38	4.00
35	35	6.77	2.23	Weak Agreement	6.67	5.73	6.50	7.67	8.11	6.00
36	35	7.26	2.17	Weak Agreement	5.50	6.36	7.33	7.33	8.44	9.00
37	36	7.00	1.89	Agreement	6.67	6.91	6.22	6.67	8.11	7.00
38	36	4.92	2.48	Weak Neutral	2.67	5.45	4.56	4.67	5.22	7.00
39	36	7.11	1.76	Agreement	7.67	6.55	7.67	7.00	7.11	7.00
40	36	7.69	1.76	Agreement	8.33	7.18	8.78	7.67	7.00	8.00
41	33	6.39	2.49	Weak Agreement	7.33	5.80	7.67	6.00	5.25	8.00
42	35	5.49	2.03	Neutral	7.67	6.09	4.33	5.00	5.33	5.00
43	35	6.97	1.90	Agreement	6.33	7.09	7.00	6.00	7.44	5.00



C.3 Workshop coding themes

Summary of the themes used to code the stakeholder workshops

Themes	
What are the benefits of current VM?	TA ,
Technical Review	TA1,
Right Solution	TA1-1,
Technical input before scoring workshop	TA1-2,
Technical consistency	TA1-3,
Technical Compliance	TA1-4,
Achieves Objectives	TA1-5,
Auditable	TA2,
Demonstrate efficiency to ORR	TA2-1,
Front-ending of design before VM	TA3,
Commercial Review	TA4,
Scoring / prioritisation	TA5,
What are the issues with the current system?	TB,
Outcomes	TB1,
Contractual	TB2,
Policy	TB3,
Operation of the system	TB4,
Value for Money	TB5,
Input information	TB6,
Scoring	TB7,
Implementation in tools and documents	TB8,
Efficiency	TB9,
Programme	TB10,
What are the desirable characteristics of the new system?	TC,
Ownership	TC1,
Who currently owns VM	TC1-1,
Position of VM in project delivery	TC2,
Overall	TC2-1,
Solutions phase	TC2-2,
Needs phase	TC2-3,
Asset Management	TC3,
Long term strategy	TC3-1,
Output from strategy	TC3-2,
Roles of VM	TC3-3,
Links to funding	TC3-4,
Alignment with High Level strategy	TC3-5,
Purpose/Objectives of new system	TC4,
Overall	TC4-1,
Audit	TC4-2,
Consistency	TC4-3,

C.4 Workshop consensus statements

Workshop	Consensus Statement (Question and responses)	Themes
W1	Who owns 'VM'?	TA
W1	The VM process is owned by Highways England. There is a distinction between ownership of the process and ownership of the product. PTS is the policy owner and owns the document set. NDD owns the product and operation of the process (where required through the service providers) and signs off scheme value	TC1-1
W1	What is achieved by applying VM?	
W1	Identify schemes	
	Outside scope? Service provider to identify – in line with HE asset management strategy	
W1	Prioritise schemes	TA5
	Outside scope? After VM?	
W1	Identify efficiencies / cost savings	
W1	Technical compliance	TA1-4
	Confirm appropriate solution (scheme sign-off)	TA1-1
	Including H&S and GD04 assessment	TA1-5
	Including whole life cost assessment	
W1	Auditable evidence of state of asset	TA2
W1	Generate evidence (score) for prioritisation	TA5
W1	Is it useful to score schemes?	
W1	Needs to be some form of rating to inform prioritisation (not necessarily a score)	TC2, TC6-4
W1	It would be useful to keep scores separate (i.e. risk / safety inc. GD04 / VfM inc. WLC / sustainability)	TC6-4
W1	This would assist flexibility if requirements on HE change	
W1	Consider (additional) score to align with HE objectives / asset strategy	TC3-5
W1	Different asset types need different methods of appraisal?	
W1	Want consistent process for different asset types so far as possible	TC4-3
W1	Ideally would like to appraise in the same way, in practice difficult to do so – accept that different methods needed for different asset types	TC4-3

W1	May be irrelevant if individual score components are visible – use as input to prioritisation (separate from VM)	
W1	How should ‘VM’ be linked to strategic asset management?	
W1	Strategy must drive what is put forward into VM	TC3-5
W1	Strategy should need consideration of two workstreams:	TC2
	Needs’ driven	TC2-3
	Planned programmes of renewals	TC6-5
W1	VM should operate at scheme level	TC2
	Should check ‘fit’ with strategy	TC3-5
Workshop 2		
W2	<u>Who owns ‘VM’?</u>	
W2	“The VM process is owned by Highways England. There is a distinction between ownership of the process and ownership of the product. PTS is the policy owner and owns the document set. NDD owns the product and operation of the process (where required through the service providers) and signs off scheme value.”(from W1) W2: This is true based on current organisation structure. Operation of the process requires joint input from PTS and NDD to provide technical governance.	TC1-1
W2	The VM process is owned by Highways England. There is a distinction between ownership of the process and ownership of the product. Under the current organisation structure, PTS is the policy owner and owns the document set. NDD is accountable for the product and operation of the process (where required through the service providers) and signs off scheme value, with support from PTS on technical compliance. Q – accountability of PTS experts for application and consistency across regions	
W2	<u>What is achieved by applying VM?</u>	
W2	Technical assurance	TA1
W2	Demonstrate VfM – best WLC option	TA2, TA1-1, TA5, TA4
W2	Prioritise spend	TA5

W2	Provide (national) consistency	TA1-3
W2	Achieve strategic objectives (needs flexibility)	TA1-5
	E.g. Fence to fence fits within this – may result in other assets being included in schemes	TA4
W2	Identify needs and schemes	
	Outside scope of VM - service provider to identify – in line with HE asset management strategy	
W2	W2: prioritisation of schemes must be based on VM scores – real danger in not doing this (i.e. disregarding the 'expert' consensus opinion)	TA5, TC6
W2	Technical assurance	TA1-3, TA1-2
W2	Demonstrate VfM – best WLC option	TA4
W2	Prioritise spend	TA5
W2	Provide (national) consistency	TA1-3
W2	Achieve strategic objectives (needs flexibility)	TA1-5
	E.g. Fence to fence fits within this – may result in other assets being included in schemes	
W2	Is it useful to score schemes?	
W2	It would be useful to keep scores separate (i.e. risk / safety inc. GD04 / VfM inc. WLC / sustainability)	TC6
	This would assist flexibility if requirements on HE chang	
W2	Consider (additional) score to align with HE objectives / asset strategy	TC3-5
Workshop 3		
W3	Comparative factors for prioritisation	TC6-4
W3	Safety	
W3	Environment	
W3	VfM	
W3	WLC (needs further development)	
W3	Preventative maintenance	
W3	Capital (delivery) cost	
W3	Resource (development) cost	
W3	Benefit (value) of scheme	
W3	Risk / Risk of not doing work	

W3	Sustainability – overarching principle – not ranking factor (due to multiple components)	
W3	Objectives for RPP process	TC4
W3	Develop right type of scheme (match strategic objectives)	TC4-5
W3	Developing right solutions for each scheme	TC4-5
W3	Prioritise right schemes into an overall programme	TC5
W3	Robustness of process	
W3	Flexibility	TC6-1
W3	Efficient to operate	TC6-1
W3	Factors for setting strategy – what to take through VM	TC6-4
W3	Socio-economic	TC6-4
W3	Fit with RIS	TC3-5
W3	Customer needs	TC6-4
W3	Visibility (forward planning)	TC6-4
W3	Asset Mgmt strategy	TC3-1, TC6-4
W3	Network needs (5 years)	TC6-4
W3	Operating policy	TC6-4
W3	Flexibility and accountability (VM structure cannot be rigid – must allow for sensible programme-setting at regional level)	TC6-1, TC6,2, TC6-4
W3	Useability (need to consider end-user / trials / roll-out policy / longevity of guidance – not changed each year)	TC6-3, TC6-4,
Workshop 4		
W4	Benefits of VM	
W4	Consistent approach across country (potential contradiction with 'human approach' applied differently in different regions)	TA1-3
W4	Ranking process – formalised best use of limited resource	TA5
W4	Allow consideration of multiple parameters (not just the money – include environment, safety, VfM etc)	TA5
W4	Avoids overspending allocation – fit budget	TA4

W4	Allow consideration of Whole Life Cost	TA4
W4	Demonstrable process for managing assets (audit – NAO, public accounts committee)	TA2
W4	Evidence-based (to determine need)	
W4	Workshops can promote collaboration and knowledge transfer	TA1-2
W4	Opportunity for technical oversight	TA1-3, TA1-4
W4	Opportunity for contract challenge (why not done under lump sum)	TA4
W4	Allows feedback of which schemes should be taken forward	
W4	Purpose / Objective of VM	
W4	To support the programmes of renewals investment to maintain the network	
	Evaluate schemes to go into programme	TC5
	Decision support	TC4-5
	Provide balance between multiple factors	
	Align with asset management strategy	TC3-1, TC3-5
W4	Transparency and robustness of decision-making (creates audit trail)	TC4-2
W4	Confidence in decisions – assurance – confidence in supplier proposals	TC3-5
W4	Alignment with Highways England objectives	TC4-1
W4	Aim – add value through process – not just paper exercise	TC5
W4	Prioritisation and programme setting – outside of VM?	
W4	Asset Management	
W4	Knowledge and understanding of the asset	
	Includes data systems (as part of asset management)	
W4	Forward programme	
W4	Risk (of intervention / non-intervention)	
W4	Asset management – strategic level (including long term view)	
	Includes PTS role for setting asset policy	
W4	Value management – operates at tactical level	
W4	Review the spend	
	Align with Asset Management Objectives	TC3-1

	Which align with Highways England objectives	TC3-5
W4	Factors in Prioritising Work	
W4	Safety inc road worker safety	TC6-4
W4	Regulatory driver (e.g. meeting air quality legislation)	TC6-4
W4	Whole life cost	TC6-4
	Value – saving by doing works now	TC6-4
W4	Environment	TC6-4
W4	Disruption to network (revisit) – links to road worker safety	TC6-4
W4	Asset-specific factors – e.g. deterioration, immediate impact and how long is available	TC6-4
	Mean time between failures (reliability)	TC6-4
	Obsolescence	TC6-4
W4	Risk factors – e.g. Great Heck response	TC6-4
W4	Vulnerability / resilience	TC6-4
	e.g. to flooding	TC6-4
W4	Cross-asset failure impacts	TC6-4
W4	Reputation – customer perception	TC6-4
	E.g. visible deterioration / rusting	TC6-4
W4	Need (not knee-jerk reaction) e.g. safety based on risk not emotional argument (negative need)	TC6-4
W4	Customer – end user	TC6-4
W4	Social sustainability	TC6-4
W4	Political	TC6-4
W4	Reactive e.g. incident response – outside of VM	TC6-4
Workshop 5		
W5	Purpose / objectives of VM (future)	
W5	There should be a clear split between agreeing prioritised needs, and agreeing appropriate solutions. The prioritised needs must address both local needs and the overarching national objectives.	TC2-1
W5	There needs to be a consistent method of identifying / determining needs across assets / across the network. Needs will have to be ranked and prioritised. Prioritisation tools may assist in supporting this and should be applied in the needs phase not just within VM (solutions phase).	TC2-3

W5	VM should be an assessment of how well a proposed solution addresses the identified need.	TC4-5
W5	VM has a useful role as a stagegate to agree between the provider and Highways England about the solutions.	TC2-2
W5	An important part of VM is the technical review provided by PTS providing technical assurance that the right solutions are proposed	TA1-4, TC4-4
W5	VM is important in providing an audit trail for decisions, through minutes of VM workshops and SAR forms.	TA2
W5	Issues	
W5	There is potential conflict amongst Highways England's objectives – e.g. whole life cost may clash with environmental objectives, etc.	TB3
W5	Schemes have a 2-year design lead-in, therefore meeting changes to objectives may required rework to schemes	TB10
W5	Regional prioritisation cannot operate in isolation from contractual obligations, particularly expected spend in each area.	TB8, TB4
Workshop 6		
W6	Setting the programme	TC2, TC5
W6	There are 3 steps to setting the programme: Everyone agree need Decide what is right option Then do design work – re-review scheme to check still achieves objectives at acceptable price Decide when to implement scheme – form into programme	
W6	What is VM (current)?	TA
W6	'Dragon's Den' – look at competing needs, balance against available money	
W6	'Tick in the box' – a mandated process that has to be followed	
W6	Audit trail for scheme – demonstrate process followed / demonstrate value for money	TA2
W6	Current VM process is trying to do too many things at too many stages	TB4, TB8
W6	Currently not fit for purpose	TB
W6	Scoring	
W6	The VM score are currently not useful in the prioritisation of schemes.	TB7

W6	It would be useful to see the individual components (safety, VfM, sustainability) rather than combined score.	TC6
W6	However, for this to be useful demands an overall strategy against which the scoring can be compared.	TC3-1
W6	The scoring needs to be flexible to be adapted if the strategy changes.	TC3-5
W6	The safety score is not fit for purpose since it is based on historic data (reactive e.g 18-month old accident data) rather than potential future safety issues (preventative)	TB7
W6	Purpose / objective of VM (future)	
W6	Audit trail – demonstrate that money has been spent in best possible way	TC4-3
W6	Satisfy licence objectives to provide value for money based on whole life cost principles within the constraints of available budget	TC6-5, TC4-2, TC4-5
W6	Consistency across nation	TC4-3
W6	Technical review is important but needs to be carried out sufficiently early to avoid abortive design work	TC4-4
W6	Manage cost and commercial risk of schemes through updating at successive stage gates (proportionate to overall scheme cost)	TC4-7, TC3-4
W6	How should VM operate	
W6	VM should be a rolling process and should align with the 5-year RIS strategy (should not cut across it)	TC3-5
W6	VM should be a series of successive stage-gates (should not require schemes to go back to previous stage):	TC6
	Identify need through network review	TC2-3
	Determine what is right solution	TC4-5
	Develop finer detail of design including surveys and confirm cost	TCTC3
	Agree to proceed and determine timing for implementation	
W6	Need to consider risk – links to GD04	TC6-4
W6	What does ‘value’ mean?	
W6	Needs judgement on what to include in ‘equation’: e.g.	TC6-4
W6	Lane availability / traffic disruption (visibility to customers important e.g. night work)	TC6-4

W6	Serviceability of network (i.e. free from defects) – difference between customer perception and other non-visible deterioration	TC6-4
W6	Meet environmental aspirations	TC6-4
W6	Meet customer aspirations (e.g. socio-economic, including economic growth)	TC6-4
W6	Safety – e.g. accident reduction (e.g. specified prevention rate)	TC6-4
W6	New technologies / innovation	TC6-4
W6	Potentially conflicting priorities	TC6-4
W6	This links back to overarching Highways England objectives and strategy	TC6-4
Workshop 7		
W7	Needs Phase	TC2-3
W7	There is a need for a (nationally) consistent decision-making framework to support the needs phase. Currently there is a gap here. Value Management (optimisation of solution) should not operate in this space.	TC2-3
	Scoring should be rapid but based on key drivers (e.g. standard scoring chart)	TC6
W7	Value Management is not isolated and should sit as part of an overall asset management process.	TC3,
	Need asset models	TC3
	Need to support funding allocations	TC3-4
	Should support determination at DfT for funding	TC3-4
W7	Funding allocations are currently based on historic spend – this should be based on the predicted need – this would be supported by nationally consistent tools	TC3
W7	Factors to be considered in needs phase	
W7	Risk-led	TC2-3, TC6-4
W7	Safety	TC2-3, TC6-4
W7	Environment	TC2-3, TC6-4
W7	Deterioration / asset condition	TC2-3, TC6-4

W7	Customer need (e.g. complaints, MP commitments)	TC2-3, TC6-4
W7	Should all support RIS Performance Spec and Highways Englands objectives	TC2-3, TC6-4
W7	Opportunities need to be considered in programming (efficiencies – coordination of work / timing)	TC2-3, TC6-4
W7	Purpose / objectives of VM (future)	
W7	Confirmation doing right thing (i.e. right <u>solution</u>)	TC4-5
	Technical review at outline design stage (inc. buy-in to departures)	TC4-4
	Optimise solution / Value engineering / Refinement of solution	TC4-6
	Includes delivery review (is scheme deliverable)	TC4
	'Right' design being developed	TC4-5
	Need being properly addressed (primary purpose is not to revisit whether it is the right need / problem)	TC4-1
	On track with previous decisions	TC4-1
	Review potential opportunities / programming to combine with other works in same location (should be identified from needs phase)	TC5
W7	Develop outputs i.e. scope, costs, duration (roadspace impact)	TC4-5
	Right money in future budget – anticipated cost range	TC4-7, TC3-4
	Recognise that detailed design still to follow - scope and cost may vary but need to control	
W7	Short record to confirm rationale and review of solution – audit – record of decision and why	TC6
W7	Not – prioritisation	TC4-1
W7	How – what achieved through VM	
W7	Tools and effort proportionate to scale of scheme i.e. simple grading for simple schemes	TC6-1
W7	Flexibility	TC6-1, TC6-2
W7	Evidence provided appropriate to solution (e.g. not demanding evidence where solution is clear)	TC6-1, TC6-2
W7	Permit use of standard solutions (e.g. ASOP)	TC6
W7	Right people consulted	TC6-4

	Is it buildable?	
	Is it deliverable?	
	Is it the right solution?	
W7	Align with yearly timings to fit with central business planning	TC5
W7	Should provide information to support procurement decisions	
W7	Scoring	
W7	The VM scoring for renewals is not currently useful:	TB8
	Serves no purpose in investment decisions – or can cut across decisions already made	TB1, TB4
	Not comparable across assets	TB4
	Not consistent across country – different interpretations by specialists / subjective scoring by service providers	TB8
	Does not capture all relevant issues – e.g. roadspace issues	TB1
W7	It can be used to compare alterative options for the same asset type	TC4-1
W7	Scoring is not viewed as essential to VM – even for audit – could be satisfied by decision record	TC6
W7	Issues with VM	
W7	Does not offer value in current form	TB1
W7	Ends up justifying decisions already made	TB4

Appendix D

Supporting materials for visual inspection study

D.1 Example Benchmark Inspection Record

PARSONS BRINCKERHOFF WSP

Benchmark Inspection Record

Parsons Brinckerhoff Staff:	John Bennetts	**Site Visitors / Incidents**	None / none
Bridge:	A Bridge	**Highways Area:**	Area G
Structure Key:	17975	**Dates:**	30/09/15
Weather / temperature / conditions	Dry, 12°C	**Night / Day**	Night

Instructions

This form is to be used by Parsons Brinckerhoff staff to record State of Bridge Infrastructure Inspections. The information collected will feed into a report which will make recommendations covering the following areas:

1. Reliability of Principal Inspection data
2. Best practice for the **design** and **construction** of bridges for future durability, ease of maintenance and inspection.
3. Best practice for the maintenance and management of bridge assets.

Sections below should be filled out as fully as possible giving your best judgement as an experienced bridge inspector. Our role is to impartially and accurately record current practice, the data recorded will be a combination of facts and your opinion/judgement.

The data to be gathered is organised into the following sections:

1. Inspection details
2. Reliability of inspection data
3. Bridge Design and Construction
4. Bridge Maintenance and Repairs
5. Independent inspection and scoring of selected elements

1 – Inspection details

Principal Inspection

Data required	Response
Duration of witnessed works (Start/Finish)	21.40 – 22.15
Duration of the PI if in addition to the shift observed?	Additional 15mins (21.25 – 21.40) while witnessing testing team at next structure .
Was sufficient time allowed for the inspection?	Yes – ample. MEWP works at three bridges during a full night shift.
Was the Benchmark Inspection completed in full? (Please give details if not, including best estimates of when it will be completed)	Yes, although non-MEWP elements had already been inspected prior to this visit.

Service provider's Inspectors (names / companies)	Joe Bloggs, A contractor ltd.
Equipment used for inspection	Camera, hammer, notepad, head torch.
Equipment used for access	T20 type MEWP
Traffic Management deployed (Give details)	Full eastbound road closure of the A30. TM provided by Area 1 staff.
Is smart technology or monitoring being used on the bridge, or as part of the PI? (Brief details?)	No.

Testing

Data required	**Response**
Duration of testing as witnessed (Start/Finish)	Partial witnessing of testing 20.45 – 21.30
Was the testing curtailed? (Details)	No – all elements of scope document undertaken.
Testing resources (personnel / equipment/ company)	Testing company ltd.
UKAS Accreditation?	Yes
Testing undertaken according to scope? Were adjustments made to the testing scope/locations on site?	2 x 1 undertaken to N pier, traffic face and S pier, traffic face. No data logger, h/c readings read out and written down. All readings +ve or low –ves. Testing as stated in scope. Appeared competent and efficient.

2 – Reliability of inspection data

Data required	Response
Were the service provider's resources suitable?	Yes – 2no persons in attendance
Was the inspection to BD 63? (why not?)	Yes – within touching distance.
Was the inspection in the spirit of BD 63? (why not?)	Yes – thorough.
Is any guidance being referred to by the inspectors on site? E.g. Bridge Inspection Manual, defect codes, etc	Yes – file containing previous inspection information to hand in MEWP throughout.
Are there structural elements for which data will not be collected? Why?	Only witnessed high level inspection, during which all elements were inspected. Other parts of the structure inspected previously.
Have the inspector(s) undertaken a structure review prior to starting the inspection?	Yes – previous inspection reports reviewed and discussed by inspectors prior to commencing.
Are there known defects that are being targeted?	Impact damage above lane 1, westbound carriageway.
How could the inspection process be improved? (Brief details)	Better lighting.
Could the inspection or testing be carried out more efficiently?	Less time spent on overly thorough delamination survey.
Has anything prevented the inspection team from undertaking the inspection better? e.g. access, time limits, network availability, other site specific restrictions.	Not particularly. Better lighting as detailed above may help.
Were the testing results as would have been expected from visual clues?	No indication of problems. H/C results suggest no issues to be expected.

Are the inspectors aware of any monitoring that is required on the structure? Is the monitoring being carried out at the required intervals?	No monitoring beyond 2yearly inspections is undertaken to this structure.

3 – Bridge Design and Construction

Data required	Response
Are there areas of the bridge that are performing significantly differently to others? If so, please describe the difference and try to suggest likely cause, considering the exposure and susceptibility of details.	No.
Are there structural details that are difficult or impossible to inspect? E.g. voids in the deck. What would make inspection easier? E.g. Access hatches, safety rails, inspection gantries, etc.	No – all elements inspected.
Is there evidence of poor water management leading to deterioration of the structure? Does water management appear to have been considered in the design?	No – no evidence.
Is there evidence of poor quality of construction causing or exacerbating deterioration of the structure? E.g. low cover, premature repairs, honeycombing, etc.	Construction appears good – no defects caused by poor construction methods noted.

4 – Bridge Maintenance and Repairs

Data required	Response
Have maintenance actions been checked for relevant components? Have the inspectors checked that they have been carried out? Cleaning, greasing, torqueing, etc.	No maintenance actions raised during previous PI. Routine maintenance (vegetation cutting etc) does not appear to have been undertaken.
Is any maintenance taking place at the same time as the PI?	No.
Is there evidence of previous repairs to the structure? What was done? How are the repairs performing?	None required.
Has maintenance of water management systems been adequate? Has it been repaired or improved?	No evidence of maintenance but appears to be working effectively.

5 – Independent Scoring of Selected Elements

Parsons Brinckerhoff's bridge inspectors are to undertake an independent assessment of selected components of the bridge that they can get to 'within touching distance'. This data will be used to assess the reliability of visual inspection data and the consistency of grading by different inspectors employed by the service providers.

The likely cause of defects should also be recorded - this will be used to identify common causes of defects which will be used to inform future design guidelines.

Component	Location	Defect Code	Extent Code	Severity Code	Comments: (Note probable cause and photo ref)
e.g. Beam 1	e.g deck	RCCr	SC	D3	e.g. chlorides in water leaking from failed deck joint. Photo1.jpeg
Deck slab soffit	Above lane 1 of westbound carriageway	AD	SB	D2	Impact damage to deck edge. No exposed rebar. Not worsened since previous inspection. Photo 01
Deck slab soffit	Above central reserve	ER	SB	D2	Spalling exposing reinforcement. Photo 02.
Embankments	All	Veg	SD	X2	Overgrown vegetation. Photo 03, 04.
Piers	All	Graf	SB	A2	Graffiti to piers. Photo 05.

PARSONS BRINCKERHOFF WSP

Benchmark Inspection Record

Component	Location	Defect Code	Extent Code	Severity Code	Comments: (Note probable cause and photo ref)
e.g. Beam 1	e.g deck	RCCr	SC	D3	e.g. chlorides in water leaking from failed deck joint. Photo1.jpeg

D.2 Coding schema applied to the Benchmark Inspection Records

Codes applied to the Benchmark Inspection Records in Dedoose.

KEY QUESTION		NOTES
KQ 01	Can guidance on design for durability be improved	
	1 - Defect Causes	
KQ 03	Do designs adequately consider maintenance and inspection needs?	
	1 - Ease of Inspection	
	1.1 - Hidden details	
KQ 04	Do designs adequately consider water management	
	1 - Performance of water management	0 inadequate 5 excellent
	2 - Adequacy of maintenance to water management	0 inadequate 5 excellent
KQ 06	What are the trends in quality of construction?	
	1 - Evidence of poor quality of construction	Scored from 0 for no evidence, to 5 for strong evidence.
KQ 08	How reliable are inspection results? Is there variation in practice that can be addressed?	
	1 - Quality of inspection	
	1.1 - Carried out in accordance with BD63	
	1.2 - Carried out in the spirit of BD63	
	1.3 - Structure review prior to inspection	
	1.4 - Are defects being targeted?	
	2 - Improvements to Inspection	
	2.1 - Efficiency	
	2.2 - Access	
	2.3 - Equipment	
	2.4 - Network Availability	
	2.5 - Technique	
	3 - Testing	
	3.1 - Testing results as expected from visual	
KQ 11	Should the approach for inspections be targeted towards particular structure types and risks?	
KQ 13	Is there sufficient guidance regarding diagnosis of the cause of defects?	
	1 - Use of guidance on site	Evidence of use of guidance on site. Scored from 0 to 5, with 0 being no use,
KQ 14	Is there a need to do more to ensure the competence of inspectors?	
	1 - Suitability of inspectors	5 for 'yes' suitable. Other answers scored based on judgement
KQ 16	Are there trends in performance of different maintenance interventions which can inform future decisions/prioritisation?	
KQ 17	Is the opportunity being taken to carry out maintenance at the same time as other network interventions and schemes?	

KEY QUESTION		NOTES
	1 - No maintenance being carried out along with PI	
	2 - Details of maintenance being carried out during PI	
	3 - Are inspectors aware of maintenance needs?	
	4 - Has maintenance from last PI been carried out?	
	4.1 - Yes	
	4.2 - No	
KQ 22	How effective has previous maintenance been in practice?	
	1 - Performance of repairs	Evidence of performance of repairs 0 for poor 5 for excellent
KQ 26	How long do common components last? Are adequate plans in place to predict timings of renewals?	
	1 - Are there different areas of the bridge that are performing differently?	
	1.1 - No	
	1.2 - Details of differences	
KQ 28	Is smart technology being used to inform maintenance effectively?	
	1 - Smart monitoring	
	1.1 - No evidence of Smart Monitoring	
	1.2 - Details of Smart Monitoring	
	1.3 - Opportunity for monitoring	
	2 - Monitoring Inspections	
KQ 30	Are there particular standards or processes that are preventing best practice or service for the network and its customers?	
	1 - Limitations on carrying out a better inspection	
	1.1 - Processes	
	1.2 - Standards	
00	Great Quotes	